SAN ANDREAS FAULT IN SOUTHERN CALIFORNIA

A guide to San Andreas fault from Mexico to Carrizo Plain

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SAN ANDREAS FAULT IN SOUTHERN CALIFORNIA

A guide to San Andreas Fault from Mexico to Carrizo Plain

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CONTENTS

"The farther we are from the last earthquake, the nearer we are to the next"... Bailey Willis

PREFACE

This timely guide has been compiled and published as a joint effort between the California Division of Mines and Geology and the Cordilleran Section of the Geological Society of America in an effort to provide a greater understanding of the San Andreas fault and the regional tectonics of Southern California at a time when earthquakes and seismic hazards are of keen interest.

The organization, format, type style, and review of articles were planned to allow rapid printing in order to have the report available at the March 1975 meeting. Each contributor was asked to write his article, have it reviewed by 2 colleagues, and then to type it in camera ready form according to a set of specifications sent to them by CDMG. To accommodate the large number of papers, and still keep the size of the report within limits that allow quick lay-out, printing, and binding, authors were asked not to exceed 8 camera ready pages with photographs, maps, figures, and tables included.

Hopefully these contributions and the knowledge gained from the field trips and technical sessions of the 1975 annual meeting of the Cordilleran Section of GSA will better enable geologists to fulfill their professional obligations as society attempts to reduce casualties and monetary losses from earthquakes.

Too often, the information obtained by college and university researchers remains in "erudite" publications, unused by designers and planners busy with "practical" matters. Fortunately, this absence of interchange is being replaced by active dialogue between researchers and practitioners of geotechnology. This special report is intended to be one such interchange.

James E. Slosson

James E. Slosson
State Geologist

ECTION 1
egional Considerations

See caption-reverse side....

KEY PLACE NAMES

carrizo, el -- common reed grass. The plant exudes a sap from which the Indians made their sweetening substance, panoche.

cajón, el -- large box, case; Chilean, ravine or narrow canyon. The term was used to describe boxlike canyons.

tejón, el -- badger; yew; round gold ingot. The name was applied to Tejón Pass when an exploring party found a dead badger there.

Photo 1. ERTS photoimage of part of Southern California. San Joaquin Valley in upper left corner, separated from Antelope Valley by Tehachapi Mountai San Andreas fault and Garlock fault are clearly visible. Los Angeles, much of Orange County, and Palos Verdes Peninsula are in the lower rig corner; San Fernando Valley in lower center; and Ventura and Oxnard in lower left. The traces of San Gabriel fault and Clearwater fault are visible in San Gabriel Mountains. North is slightly left of the top o the photo. ERTS photo E-1090-18012-5, 21 Oct 1972.

THE SAN ANDREAS FAULT IN SOUTHERN CALIFORNIA

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RACT

he active San Andreas fault rs southern California on the hwest from the Coast Ranges, ls sharply, and then extends quely across the Transverse es to the Cajon Pass - San onio Pass region. From here, h and south branches along with Banning fault, converge on heastward and form a complex em in the Salton trough. In tion, the San Jacinto fault ds southeastward to the Gulf alifornia from the Cajon Pass on. Along the San Andreas t system, the crust to the west oving relatively but irregu- y northwestward at rates een 2 and 5 cm/yr (about 3/4 to 2 inches/yr) as shown by etic measurements. Earth- es and steep slopes along these ve faults pose engineering and omic problems for Californians ng near them.

uring Pliocene time, the San iel fault was probably the most ve strand of the San Andreas em. A distinctive terrain con- ing of many rock types in the time sequence has probably offset a total of at least 300 about 190 miles); about 60 km ut 38 miles) between the Tejon region and the Soledad Pass on on the San Gabriel fault, and t 240 km (about 150 miles) een the latter region and the opia Mountains northeast of the on Sea. Basement rocks and lying strata older than upper- Miocene have been displaced same amount, indicating that t slip on the combined faults began about 12 m.y. ago. Sedimentary basins, such as Pliocene Ridge Basin, were formed during these tectonic movements; offset features progressively younger than late Miocene are displaced progressively less on the system. With the opening of the Gulf of California a few million years ago the Transverse Ranges were elevated and some of the older structures that had been previously displaced laterally were rejuvenated vertically. Preliminary information suggests that during late Cenozoic time there was a broad transform belt across southern California consisting of subparallel near-vertical faults separating blocks of crust. During relatively northwestward movement of the Pacific plate first one fault was active, then another, and within this pattern some blocks were squeezed upwards while others sagged or were stretched and pulled apart.

INTRODUCTION

California's scenic variety results from its position in the mobile tectonic belt at the boundary between the Pacific and North American lithospheric plates. The master fault within this belt is presently the San Andreas but this has not always been so. With its branches and related faults the San Andreas is now the principal crustal discontinuity in the broad transform zone where the Pacific plate moves relatively northwest with respect to the continent. Many of these faults are seismically active and complex; crustal blocks are moving irregularly, sideways, up and down, and obliquely. Moreover, the blocks beteen the major faults, although many kilometers wide and deep, are not all rigid and strong, but are pliant. Mountains rising within this mobile belt are sculptured by stream, wind and sea erosion. Sediment carried from rising highlands spreads across lowlands, to form broad valleys and sweeping alluvial fans. Folding, faulting, jointing and rifting have operated within California at many scales and at different times at different places, as have volcanism, plutonism, metamorphism, and sedimentation. So even though we single out the San Andreas fault and its major branches for examination in this guidebook, we must appreciate that the faults are just a part of a complex tectonic scheme, and the result of powerful internal forces functioning deep within the earth.

The purpose of the field trip is to examine faults of the San Andreas system at selected localities in southern California in attempts to understand its characteristics and history. Inasmuch as Californians must live with the faults and their earthquakes, along with the resulting steep slopes it is especially important to understand the fault system for wise building and engineering construction. In addition, basic research into the origin and history of the fault is indeed needed; views differ on the magnitude and timing of its strike-slip displacements and its tectonic significance. Much remains to be learned.

We can most easily understand the present tectonic behavior of California because we can study earthquakes and measure instrumentally the way that the ground is now deforming. Accurate surveys and tiltmeters, for example, reveal continuous crustal movements. During times of earthquakes we obtain readings on sudden local displacements. Western California is unevenly and relentlessly gliding relatively toward the northwest along faults with the San Andreas system at rates to 5 cm/yr (2 in/yr)(Hofmann, 1968; Savage and others, 1973). Crustal blocks, caught in this movement, are distorting -- ben- ing, rising, and sinking. The Imperial Valley region near the San Jacinto fault zone in parti- ular is being distorted; earth- quakes such as the Borrego Moun tain Earthquake of 1968 (Sharp others, 1972) demonstrate activ tectonic instability. Althoug much of the San Andreas fault s tem is seismically active both this southeastern region as wel as in central California (Brow and others, 1967; Kovach and N 1973), the San Andreas fault i the northcentral Transverse Ra at its Big Bend near Gorman (F 1) has not had a major earthqu since 1857. This 1857 Fort Te Earthquake, with an epicenter where along the fault zone in Tejon Pass region (Wood, 1955) was as severe as the infamous Francisco earthquake of 1906. over, present geodetic measure reveal little distortion along fault in comparison to regions north and south (Savage and ot 1973). As Allen (1968) has su gested, the San Andreas is now "locked" in the Big Bend. Str is perhaps primarily released by major earthquakes from time time rather than by creep and many small quakes along the fa as elsewhere. In the Transver Ranges, as shown by the San Fe do Earthquake of 1971 (Grantz others, 1971), seismic activit seems to be more closely relat north-south shortening and mou uplift, than to San Andreas ty motions.

Geophysicists and geodesists presently documenting the natu the mobility and flexibility o California. More and better instruments, however, are need

ument more satisfactorily defor-
ion in California at present.
h studies on a world-wide scale
ng with geologic information
necessary to elucidate plate-
tonic theories which have re-
led that thin crustal shells and
underlying upper mantle of the
th have been spreading apart,
verging and sliding by each
er, for millions of years to
duce most of the geologic and
graphic features evident on a
bal scale. Refinement of these
te-tectonic theories, however,
their application to problems
direct human and engineering
cern in California as elsewhere,
end as well on detailed tec-
ic studies back into geologic
e.

Landforms in southern Califor-
reveal much concerning tecton-
history, and extend our under-
nding back into prehistory for
y millenia. Fault scarp and
set streams, for example, show
places the results of several
ements. This evidence leads to
conclusion that displacements
most of the great faults have
urred through time. But, ex-
t in a few instances, we have
tle data on intervals of recur-
ce (Wallace, 1970). More geo-
phic research is needed, cou-
d with studies of erosion and
imentation across recently
ive faults. Deposits laid down
sag ponds at the base of fault
rps can perhaps be dated by iso-
ic methods (C_{14}), by palynolog-
l studies or by volcanic-ash
onology using fission-track dat-
and trace-element techniques,
thereby place time limits on
origin of these fault-formed
tures in the near geologic past.
interesting geomorphic charac-
istic of the San Andreas fault
that it obliquely transects
eral major topographic features
California, such as the San
Gabriel Mountains, where the fault furrow shows little relation to the gross topography. At places the San Andreas fault lies at the base of high escarpments facing northeast (for example, south of Antelope Valley, the western tip of the Mojave Desert), or facing southwest (at the base of the San Bernardino Mountains near the city of San Bernardino).

Farther back in time, our understanding of fault movements depends upon geologic relationships of offset rocks and sedimentary basins over broad regions on either side of the faults. At places sedimentary rocks of Late Cenozoic age laid down at the base of a fault scarp are now offset laterally many kilometers from their source areas. These offset prisms of sedimentary rock range in scale from the truncated distal ends of Quaternary alluvial fans, to middle and late Tertiary basins. Early Tertiary strata, deposited prior to the inception of the San Andreas fault, have been transected by faults so that facies are now displaced hundreds of kilometers (Hill and Dibblee, 1953; Addicott, 1968). Distinctive crystalline basement terrains have also been cut by the faults and displaced -- laterally, vertically, or obliquely. But modern studies that fully characterize and identify these rocks, through the use of geochemical, isotopic, petrographic, and paleontologic methods, are still incomplete, and opinions vary on the significance of results obtained so far. We can conclude at present, however, that the history of the San Andreas system has been long and complicated.

A principal purpose of this field trip is to look briefly at the kinds of evidence bearing on the geologic history of the San Andreas system. We will examine the nature of the highly deformed rocks within the San Andreas fault zone, the landforms such as scarps and sag ponds along the fault, and discuss the difficult decisions facing Californians in living with the faults. These decisions, although they must be based on geologic understanding, require considerations of engineering, economic, sociologic, and other factors. Geophysical and geodetic data, although vital to our total understanding of these problems, are less emphasized in our discussion because these data are better represented by diagrams, graphs, maps, computer print-outs, tables, and equations that are better studied in an office. However, geophysical investigations are reviewed in articles within this guidebook.

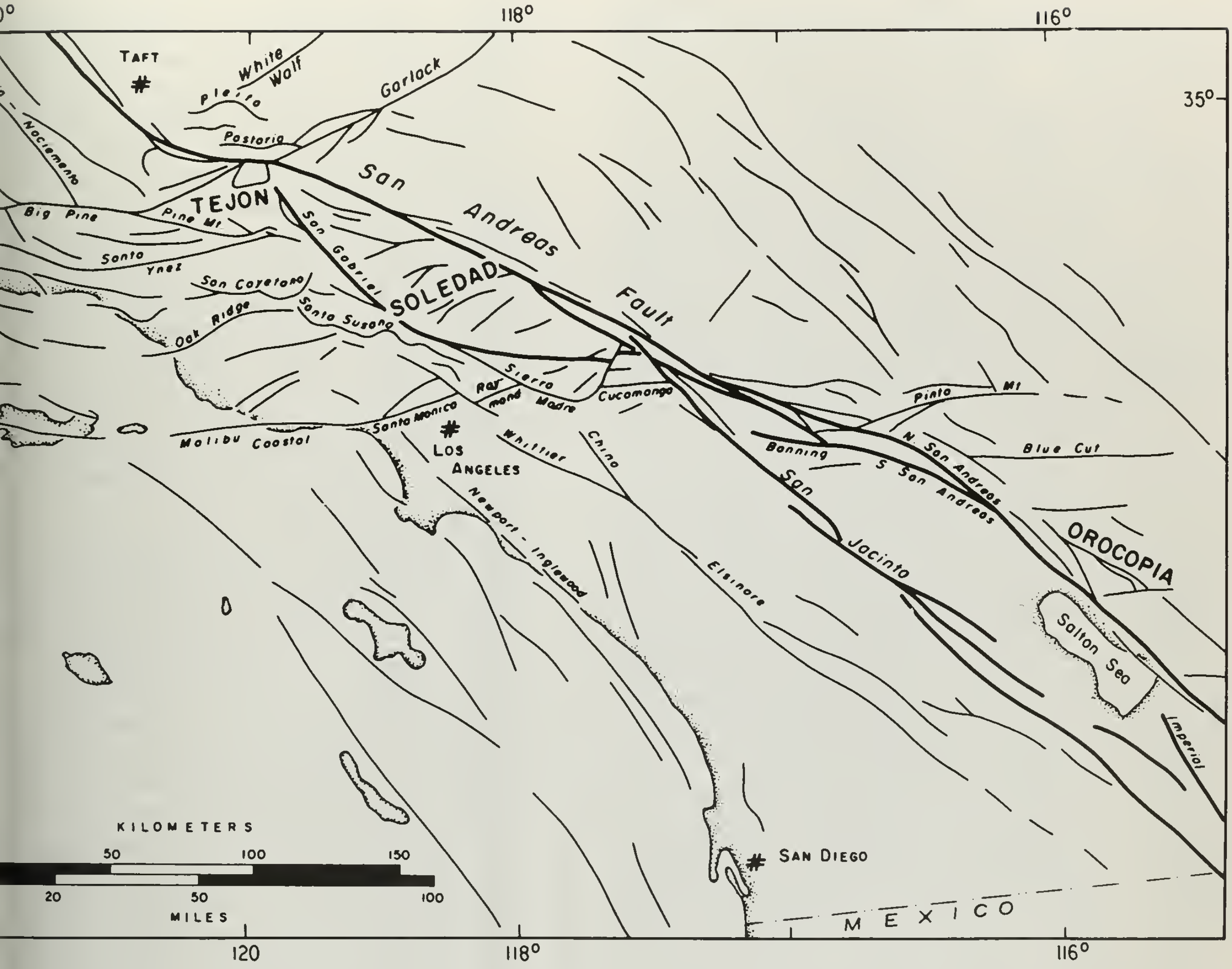
The remainder of this introductory article reviews the status of answers to basic questions concerning the San Andreas fault system in southern California. Such questions are: What is the San Andreas system? When did it originate? How have faults within it moved through time? What has been their total displacement? And finally, what is the role of the fault system in the tectonic framework of western North America?

WHAT IS THE SAN ANDREAS FAULT?

The San Andreas fault system is a set of extensive high-angle faults striking northwesterly and trending through California for about 1000 km (625 mi.) (Fig. 1). Faults of the system are considered to be late Cenozoic strike-slip faults, or at least to possess low-angle oblique slip. The name San Andreas fault is applied to the principal, most recent surface of rupture. As a fault, it is a discrete fracture at places and a narrow belt of fractures at other places that dip nearly vertical; it has a relatively straight tr across the terrain. It is a de discontinuity within the earth' crust extending downward 7 to 1 km (4 to 8 mi.) to a zone where rocks mainly flow plastically under stress instead of fractur brittlely. As a crustal break, it is the result of powerful earth forces, and itself does not cau earthquakes. Earthquakes are largely sited along faults, tha they occur along the boundaries o crustal blocks as these are forc to slide by each other. As the forces build up through time, the blocks stick together until the sticking point is passed; they then suddenly slip by each othe at the fault to release the str causing the earthquake.

The San Andreas fault is a nearly continuous fault zone o roughly parallel fractures th branch and interlace in a band much as 10 km (6 mi.) wide. Ro of many types within this zone severely deformed and minor st tures within the zone are loca quite chaotic. Because of int deformation within the fault z the rocks are soft and easily eroded, so that its course is commonly marked by a broad and shallow trough within which is array of recent fault landform such as fault scarps, slices, ponds, and shutter ridges (Sha 1954). This topographic troug with its associated fault land forms is often referred to as San Andreas rift -- a topograp or geomorphic term, rather tha structural or tectonic term.

Some major faults with tren subparallel to the main San An fault zone lie to the west. T include the Elsinore, Whittier faults along the Newport-Ingle zone, and some faults offshore the California Borderland. Al



1 -- Some major faults in southern California. Tejon, Soledad, Orocopia are three regions of similar terrain considered as dis-
ed on the San Gabriel -- San Andreas fault system.

gh they may properly belong to San Andreas system, for con-ence of scope they are referred nly briefly in this guidebook. of these, and including some ne northeast of the San Andreas t as well, have not yet been ied sufficiently to be sure they are late Cenozoic strike- faults; at present they can be gned to the San Andreas system tentatively. Some may be l to be older and with differ- lisplacement styles; they will to be excluded from the sys- Faults with a northeast-south-west or east-west trend, such as the Garlock, Big Pine, Santa Ynez and Malibu Coast - Cucamonga, are not here included in the system, although they may be tectonically related.

North of the Transverse Ranges, the San Andreas fault trends nearly continuously to the ocean north of Point Arena, and then along the sea floor to its intersection with the Mendocino Escarpment. Through the central part of the state, it is remarkably straight, but in the vicinity of Hollister, the San

Andreas fault bends slightly westward where two major branches splay northward: the Calaveras-Sunol fault and the Hayward fault. Within the Transverse Ranges, and extending southeastward, the San Andreas fault system is more complex. Near the northern edge of these ranges near Gorman, for example, the fault zone bends sharply -- termed the Big Bend -- and trends east-west for about 10 km (6 mi.) between its junctures with the Big Pine and Garlock faults. Southeastward, there are several major branches; these include the San Gabriel fault (the principal fault of the system during Pliocene time) and the San Jacinto (a major component of the system today (Sharp, 1967). In San Gorgonio Pass, farther to the southeast, the recent break intersects the Banning fault at the surface (Allen, 1957) although the principal discontinuity occurs along a more ancient break -- the Mill Creek - Mission Creek fault. Here is another region where the fault trace bends, and where other faults meet the San Andreas at a high angle: for example, the Pinto Mountain fault. In such cases, the identification of the San Andreas becomes increasingly unclear. In the San Gorgonio Pass region, some geologists consider the San Andreas proper as ending against the Banning fault; others have renamed the Mill Creek - Mission Creek fault as the northern branch of the San Andreas (Dibblee, 1970). It is well to emphasize the concept of a system of faults and to visualize a broad and braided zone of subparallel faults moving through time. As one strand takes over the movement, another is abandoned.

Concepts from plate tectonic theory help us in picturing how the San Andreas fault system ends, to the northwest and southeast. If considered as a transform fault at present, it ends on the north a triple junction near Cape Mendo where the Pacific, North Americ and Juan de Fuca plates interse (Atwater, 1970). On the southe it passes into the Salton Troug and Gulf of California and appa ently becomes involved with sea floor-spreading mechanisms considered as responsible for spli ing off of the Baja California Peninsula from the North Americ continent. According to this v the fault is a right-slip fault ending at the northern end of t original rift that later widene form the Gulf of California (Crowell, 1974a, Fig. 3). Sout-east of this point, rocks of th continental crust have been pule apart from their counterparts across the widening trough and From here, it no longer is a t fault with two walls snug agai each other, but is a continent margin. Local structures resu mainly from down-slope sliding the widening chasm. Although a simple transform view may ap to the fault zone at present, has existed for at least 8 or m.y. before the present Gulf o California opened. Geologists yet to reconstruct a satisfact plate tectonic model for its b and evolution through time. S eral geologists do not apply t transform term to some contine strike-slip faults (Hill, 1971 1974) but apply it only to oce faults according to its origin usuage (Wilson, 1965).

The fault now called the Sa Andreas was first recognized i the San Francisco Bay region b several geologists in the earl 1890's: J. C. Branner, A. C. Lawson, D. S. Jordan, H. W. Fa banks, C. Derleth, Jr., and S. Taber. The fault, first name S Andreas by Lawson (1895, p. 46) had been traced for some 400 k (250 mi.) southward from the S

cisco region before the earth-
of 1906. In southern
fornia, Fairbanks (1894, p.
briefly described the fault
e Big Bend region and later
ler (1897, p. 711-713) des-
d and illustrated it; but
er geologist named it. The
San Francisco earthquake drew
attention to it, after which
s traced northward and follow-
uthward into the Salton
ssion (Lawson and others,
.

DID THE SAN ANDREAS FAULT
RIGINATE?

deciphering the complex rock
d in California as it bears
e history of the San Andreas
m, we have to approach two
questions more or less
taneously: when was the fault
? and what is its total dis-
ment? In finding the maximum
, rock units and structural
ds predating the birth of the
t must be identified and
lated with their displaced
terparts; this involves dis-
uishing between rock bodies
ating the fault from those
d after the system originated.
ral continental basins and sed-
tary stratigraphic units in
ern California, for example,
t show the total slip on the
m because they originated
after the movements began.
units include Pliocene rocks
idge Basin.

o methods, supplemented by a
, are available to date the
of faults of the San Andreas
m. First, if a scarp is
d at the surface as a conse-
e of a dip-slip component,
entary rocks may be deposited
the scarp with their facies
olled by the fault. If these
its are preserved and are
le by paleontological or other geochronologic methods, they may document early fault displacement. More commonly, however, such fault-controlled facies present evidence of later movements rather than earlier movements. Examples are provided by the Upper Miocene Santa Margarita breccias, southern Temblor Range (Fletcher, 1967; Vedder, 1970), the Mio-Pliocene Violin Breccia, Ridge Basin, along the San Gabriel fault (Crowell, 1962, p. 39; this volume), and the Miocene Coachella Fanglomerate (Allen, 1957, p. 323; Petersen, 1973, this volume).

Second, along major faults with continuous or intermittent displacement through time, the magnitude of the displacement increases with age, until all rocks older than a certain age show the same displacement. If this date can be determined adequately, the time of the fault is shown (Crowell, 1962, p. 42; Grantz and Dickinson, 1968, p. 117; Huffman, 1972, Fig. 13). In southern California the geologic record is unusually complete with many potentially datable rock units of many ages.

Third, as confidence in the tenets of sea-floor spreading and plate tectonics increases, geologists and geophysicists are beginning to extrapolate movements inferred from knowledge of the Pacific Ocean floor to movements at the broad juncture between the Pacific and Americas plates. Atwater (1970) fairly successfully reconstructed events in California using the pattern of magnetic anomalies on the sea floor as a springboard for her interpretations. Later movements on the San Andreas system as judged from the land geologic record dovetail reasonably well with her interpretations, although the middle and early Tertiary record does not accord very well. It seems likely that as more knowledge is gained of tectonic movements in western North America during Mesozoic and early Cenozoic times, our knowledge of plate-tectonic theory and its application will be improved. A satisfactory tectonic synthesis of southern California, however, is still not at hand.

In applying these methods to southern California to date the beginnings of the San Andreas fault system, it appears that it is not older than late Miocene (about 12 m.y.) and certainly not older than late Oligocene (about 28 m.y.). On the combined San Andreas - San Gabriel fault system, the Mint Canyon and Caliente sedimentary formations were deposited in a trough that spread southwestward from source areas now in the Orocopia - Chocolate Mountain region (Ehlig and Ehlert, 1972; Crowell, 1973). These formations are displaced the same amount (about 300 km or 190 mi.) as are all of the many other correlatable units recognized across the San Andreas fault system (Crowell, 1962; 1973, see below). It is therefore inferred that major right-slip movements began during late Miocene time. The only tentatively recognized exception to this conclusion follows from the occurrence of coarse sedimentary breccias assigned to the Sespe Formation in Canton Canyon, southwest of the San Gabriel fault which are about 28 m.y. old (Crowell, 1962; Bohannon, this volume). Although field relations are somewhat obscure in this area, the breccias apparently accumulated at the base of a scarp along the nearby San Gabriel fault, thereby documenting the existence of a dip-slip component at that time. This segment of the fault, however, may have had an origin unrelated to later right-slip movements.

It should be noted that sati- factory conclusions concerning birth date of the San Andreas s tem depends on fitting together local geologic detail into a re gional synthesis. In addition, geologists face a conceptual an nomenclatural difficulty: alon fault zone such as the San Andr -- several kilometers wide and sisting of many rock slices sep- rated by discrete faults, and trending through the state for 1000 km -- it is likely that s of these faults and fault segme are faults not formed by "San-Andreas-type movements". Faul formed in older rocks when Cal nia was at the boundary of the verging Americas and Pacific P probably now occur within the Andreas system, but are only r identified (Hill, 1971). Faul are named and defined on the b of their present geographic po- tion, and not by interpretatio their displacements through ti After describing faults and th rocks on either side, we searc kinematic explanations, that i the "movement picture" through of how the separate crustal bl have been displaced and deform Such studies include reconstru of paleogeography based on reg investigations of widespread stratal units of restricted ag Ancient geographies can often be reconstructed when later di- placements on the great faults been considered (e.g., Sage, 1 this volume).

Geologic information now in indicates that major right sli began on the San Andreas in s California at least 12 m.y. ag It therefore considerably pre- the opening of the present Gul California, which began about ago (Larsen and others, 1968; and Buffington, 1968; Moore, 1 Earlier right-slip must be re to earlier tectonic situation

not yet been completely worked
e.g. Karig and Jensky, 1972;
l and others, 1972). North of
ransverse Ranges as discussed
in a later section, the age
e San Andreas fault may be
much older and its total dis-
ment may be about twice as

cks deposited after the San
as fault system originated
how displacements less than
aximum and these displacements
d decrease with successively
er rocks. Facies within
terrace deposits, for example,
ay small but convincing off-
Such displacements have been
ed out by Noble (1926, 1954),
ce (1949), Hill and Dibblee,
), Sharp and Silver (1971),
everal others. Somewhat older
entary units were laid down in
raphic situations in part con-
ed by San Andreas tectonics,
ave since been displaced. Be-
the geologic record in south-
alifornia is unusually com-
, as more chronologic data
in we can expect better doc-
ation of displacements of rock
laid down after the San
as system originated. In time,
ningful time-displacement
is foreseeable.

IS THE MAXIMUM DISPLACEMENT ON
E SAN ANDREAS SYSTEM?

termining the amount of slip
ults of the San Andreas system
ds first on establishing that
ock units in crustal blocks on
r side of the fault do not
, and second, on discovering
isplaced counterparts. That
e must recognize and document
match in the rocks and their
red histories, and then, we
resolve this mismatch into a
by discovering and establish-
hat a displaced terrain is
d a counterpart. Much detailed information over a huge region is needed to establish distant correlations. In addition, we need to be sure that the true counterparts have been discovered, and that the real ones do not lie at depth beneath a covering of younger sediments (including alluvium), or have been eroded away.

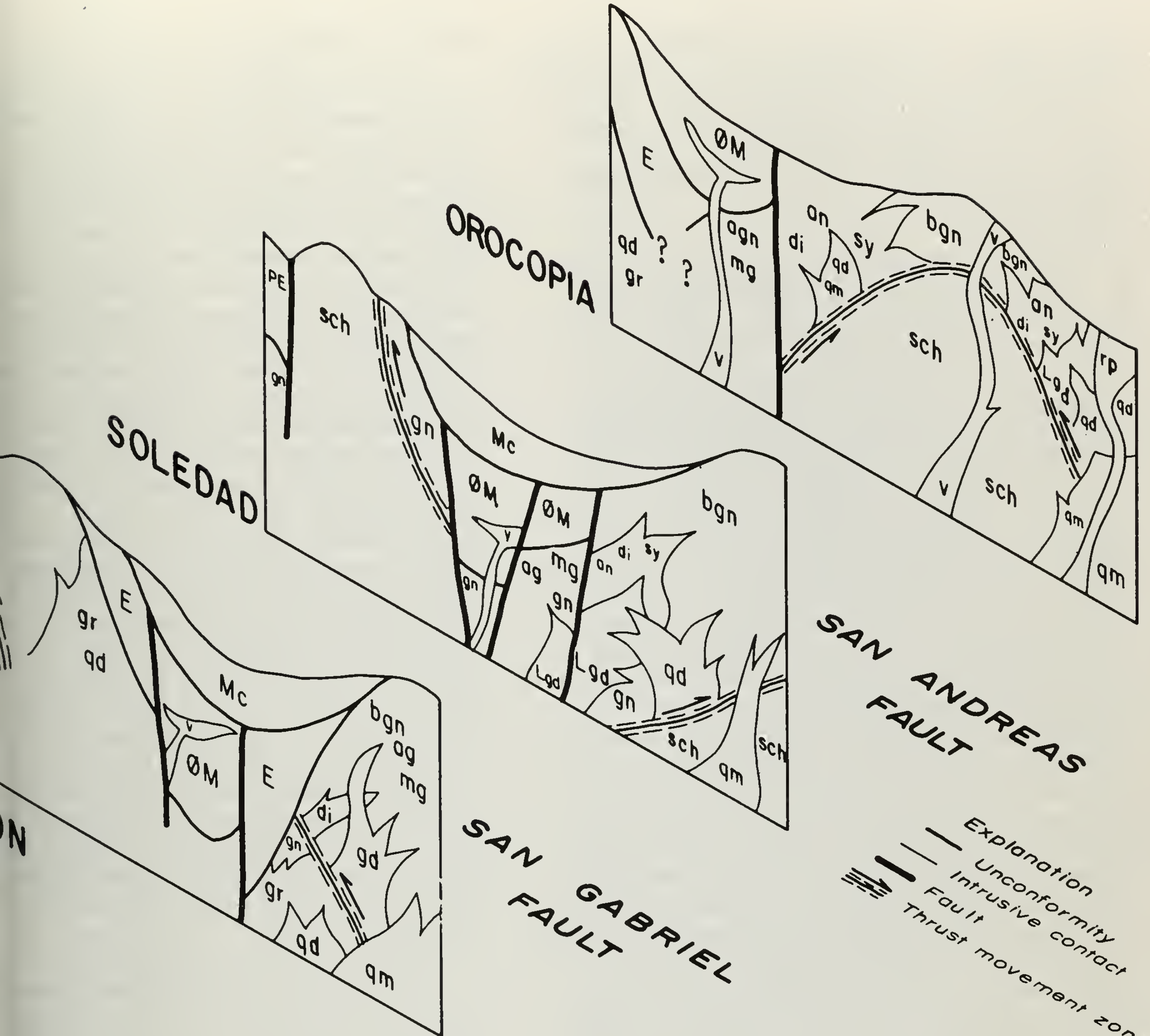
There is considerable controversy on the significance and magnitude of right slip and on its role in the tectonic scheme in southern California. For example, I interpret available data to require about 300 km of right slip on the combined San Andreas - San Gabriel and closely related faults (Crowell, 1960, 1962; Crowell and Walker, 1962). Others, such as Woodford (1960), Woodburne and Golz (1972), Baird, Morton, and others (1974) and Baird, Baird, and Welday (1974) find they can explain geologic relations with only a few tens of kilometers of right slip. The controversy hinges largely on interpretations of the uniqueness of terrains now offset, and on views of how regions crossed by the San Andreas must have appeared before displacement. The "minislippers" politely accuse the "megaslippers" of overlooking the significance of some petrochemical, stratigraphic, and structural data in rocks opposed across the faults in the Transverse Ranges, and both groups charge each other with failing to undertake sufficient scrutiny over the whole region involved in the advocated 300 km of offset and extending well beyond the "spot correlations".

Without yet understanding many aspects of the complex region, I am confident that a mobilistic view of the region involving considerable strike slip on several faults, along with deep and large-scale folding of basement as well as supracrustal rocks, some rotation of crustal blocks, and the development of pull-aparts and rhombochasms will in time explain the complexities. Such a "megamobilist" view -- that seems to emerge in part from plate tectonic concepts -- lies somewhat in contrast to the "mesomobilist" view of many, wherein less movement and deformation of individual crustal blocks through time is visualized as likely. Although perhaps such intuitions have no place in science, time will tell which "school", if either, is correct as we gain additional information. Particular attention will be paid to aspects of this controversy on our field trip.

Displaced Terrains on the Combined San Andreas - San Gabriel Fault Zones

Three terrains containing many rock types with similar petrography, age, and implied history are apparently displaced about 300 km (190 mi) (Crowell, 1960; 1962, 1973; Crowell and Walker, 1962). The basement rocks include Precambrian and Mesozoic gneisses and plutonic intrusions, greenschist-facies rocks, and mylonitic tectonic movement zones all overlain by several distinctive sequences of mid-Tertiary strata and volcanic rocks. Structures and strata with volcanic rocks, as young as early Miocene, follow trends at a large angle to the cross-cutting San Andreas -- San Gabriel system. Conglomerates as young as late Miocene contain distinctive clasts, offset from their original sources, and the sequences containing the clasts are displaced as much as all older rocks (Ehlig and Ehlert, 1972). Similar rocks are not known to occur as remnants in the wide Mojave Desert nor to lie concealed beneath young deposits. We are here concerned with remnants of basement types critical to the hypothesis as well as with source areas for some conglomerates and sediments. In t[he] accompanying isometric sketch, attention is focussed on the ro[cks,] their sequence, and their ages (Fig. 2). Space here does not [allow] detailed description of the roc[ks] in the terrain segments, nor of their histories.

Since I pointed out the prob[-] ability of these long-distant cor- relations (Crowell, 1960, 1962) in- vestigations by several geologi[s]ts have strengthened them. Radiom[e]tr[ic] dating and petrographic and che[m]ic[al] studies (Silver, 1971) have dis- closed that gneisses in the Te[jo]n Region are of about the same a[ge as] those in the Soledad Basin and [in] the western San Gabriel Mounta[in]s (1750-1680 m.y.). These rocks [we]r[e] invaded by granitic plutons (ab[o]ut 1780-1650 m.y. ago), metamorph[os]e[d] to gneisses (about 1450-1425 m.y. ago), and intruded by the anor[th]o- site complex about 1220 m.y. a[go]. In the Orocopia region the 165[0] ± 15, 1425, and 1220 m.y. episod[es] are represented by the same li[th]o- ogies. Silver (1971) has also [dated] the Lowe Granodiorite in the S[an Gabriel] region at 220 ± 10 m.y. (early Triassic). Recently I found re[m-] nants of probable Lowe Granodi[or]i[te] in the northernmost Chocolate [Mo]u[n-] tains (Orocopia region) and Jo[hn] Dillon (personal communication 1974) has found similar rocks [in the] central Chocolate Mountains (j[ust] southeast of Mammoth Wash). H[ere] these rocks have not yet been studied sufficiently nor dated [to] be certain of the correlation. Clasts of the distinctive Lowe Granodiorite have been identif[ied] in Oligocene--Lower Miocene be[ds] (Diligencia Formation) of the eastern Orocopia Mountains by [me] and independently identified a[nd] dated by Silver (1968) and iden[ti-] fied by Ehlig and me in mid-Mi[ocene] strata of eastern Lockwood Val[ley] (Tejon Region) (Silver, 1968, [p.] 280). Clasts of a distinctive



2 -- Diagram showing sequence of rock units in three regions con-
ed as displaced on the San Gabriel -- San Andreas fault system (Fig.
Not to scale. Pliocene and younger formations omitted. Symbols:
mbrian: bqn = blue-quartz-bearing gneiss, agn = augen gneiss, mg =
tite, di = diorite and gabbro, an = anorthosite, sy = syenite; Pre-
ary, but mostly Mesozoic: gn = gneiss; Lgd = Lowe Granodiorite, gr
nite, qd = quartz diorite, qm = quartz monzonite, sch = Pelona and
pia schist; Tertiary: PE = Paleocene and Eocene San Francisquito
tion, E = Eocene formations, ØM = Oligocene and Lower Miocene non-
e conglomerate, sandstone, and shale, with associated volcanic rocks,
Middle and Upper Miocene sedimentary formations, rp = rapikivi-
red quartz latite porphyry, v = other volcanic rocks.

ivi-textured quartz latite
yry occur in the upper Miocene
Canyon Formation of Soledad
Basin and in the upper Miocene
Caliente Formation of Lockwood
Valley (Ehlig and Ehlert, 1972).

The volcanic source for these stones has almost certainly been identified in the northern Chocolate Mountains, and is now being studied petrochemically by Ehlig and Ehlert. No other appropriate source has been recognized.

Some geologic units, now deformed and displaced along faults of the San Andreas system, were laid down subhorizontally. Especially in northern California, but also along the San Gabriel fault, some were deposited as widespread sedimentary units; others as more restricted in original geographic extent. Widespread or broadly and gently folded formations or structural units are displaced laterally by strike slip for many kilometers and are preserved directly across the fault at places. Under such circumstances, the horizontal slip vector is roughly parallel to the trace of the near-horizontal unit against the fault, and displacement is by trace slip on a regional scale. Cross sections drawn directly across the fault at such places show little or no vertical separation of contacts or formation boundaries as along the San Gabriel fault within the Honor Rancho Oil Field (Paschall and Off, 1961; Crowell, 1962, p. 40). Slip is determined by finding points that were originally adjacent and are now displaced, but the only feasible points are piercing points of gross lines recognized in the rocks that intersect the fault surface. Maps showing such lines are not yet available for southern California, but have been prepared by Addicott (1968) for the region along the San Andreas in central California. For limited time-stratigraphic units in the Miocene, Addicott shows offset facies lines forming piercing points at the fault, documenting about 300 km (190 mi.) of post Miocene right slip in that region. Displacement here has been by regional trace slip.

On a regional scale, blocks
separated by major faults of t
San Andreas system are not pic
tured as moving by pure strike
slip; that is, as moving with
truly horizontal-slip vector.
Blocks between converging faul
in map view are squeezed upwar
and those between diverging fa
as sagging downwards (Crowell,
1974b). All of the major faul
display a local dip-slip compo
as shown by major escarpments,
by the preservation of younger
beds in the depressed block an
their erosion from the elevate
block. In mapping areas the s
of mile-to-the-inch quadrangle,
these vertical separations are
conspicuous and are apt to be i
terpreted by some as evidence f
dip-slip primarily; others, ho
ever, interpret them as the re
of a small component of dip sl
on a fault with great strike sl
Slowly accumulating evidence i
California shows that deformab
blocks move by each other late
ally and at places are elevate
and at others depressed (Crowel
1974b).

The resolution of the contr
versy depends on (1) discoveri
and documenting linear feature
within the rocks that are olde
than the faults of the San And
system, and (2) that are cut a
displaced by them so that cha
terizing features are correla
on both sides. So far, few di
crete offset "lines" have bee
discovered across the fault sy
in southern California. A mi
Eocene shoreline (or steep bu
unconformity just offshore) p
jected on trend to the nearby
Andreas is recognizable in th
Pinos area (Tejon region), an
the Orocopia Mountains now ab
300 km (190 mi.) to the south
(Kirkpatrick, 1958; Crowell a

ki, 1959). In addition, in a s way, debris eroded from ted source areas on one side he fault, and spread out in or down valleys on the de- sed side have linear aspects, cially if attention is focussed he feather edges of the depos- Belts of basement rocks of ral types, such as those of n gneiss, blue-quartz bearing ss, anorthosite, syenite, and Granodiorite meet the great ts at an angle, but their mar- are actually steeply dipping aces. These give separations teep contacts and only the d of the masses as a whole can ictured as linear. Other units regional scale, such as the ent thrust system (including Orocopia thrust and Chocolate tain thrust) have low folded tudes. Separations shown by distribution of this disrupted st system and by that of the rlying Pelona and Orocopia sts have little strike-slip ificance because they have been laced by regional trace slip; schists are exposed within anti- s or raised blocks, and the sses and other hanging-wall s are preserved in synforms or essed blocks. .

edimentary units need special ntion by means of "basin analy- in order to find sedimentation ctions, thickness lines, facies s, and especially stone trains iagnostic type washed down from l and unique source areas. information is slowly coming and as it does, the case for r strike slip appears to be ing increasingly stronger. The e discussion emphasizes the for much information of many s, both on the basement terrains ell as on facies and petrography he overlying sediments. Corre- on studies involving rocks, ctures, and implied histories holds the key to solving the controversy. That is, are rocks now at a distance actually the same rocks that have been displaced, or are they not? Are rocks apparently the same and but little offset, actually very different? Moreover, several rock units, recognized on one side of the fault have not been discovered on the other side.

Uniqueness of the Transverse Ranges

Recently Baird, Morton and others (1974) and Baird, Baird, and Welday (1974) have assembled petrochemical and structural data within the Transverse Ranges and conclude that only a few tens of kilometers of right slip are required on the San Andreas fault zone in southern California. Their summary maps of chemical analyses and measurements of specific gravity cross the northern Peninsular Ranges and extend into the San Gabriel and San Bernardino Mountains. When contoured their data show an alignment of values parallel to the present structural grain and topography, but discontinuous across the San Andreas fault zone. In batholithic rocks, there is an irregular increase oceanward in Mg, Ca, and Fe and a corresponding decrease of K and Si Maps showing the strike of foliation in pre-batholithic and batholithic rocks and of the strike of beds and trend of fold axes reveal as well the grain of the region. Baird, Morton, and others (1974) emphasize that the province has existed with nearly its same trend since well back in time, even before the Tertiary, and that rotation of blocks sufficient to bring the terrain back into rough alignment with the Sierra Nevada, Coast Ranges, and Peninsular Anges is untenable. They view the anomalous position of the Transverse Ranges Province as a severe problem in applying plate tectonic concepts as now understood to southern California.

The uniqueness of the Transverse Ranges in western North America today is not debatable but as high mountains they are the result of very young uplift during the last few millions of years accompanied by severe deformation (Dibblee, 1968; Crowell, 1971, 1973). Plio-Pleistocene sedimentary units throughout the extent of the Transverse Ranges are folded, faulted and now elevated. This very late deformation has been termed the "Pasadenean Orogeny" (Reed and Hollister, 1936). Some of the roughly east-west depositional and structural trends west of the San Andreas fault zone, such as those in lower and mid-Tertiary rocks in the Upper Cuyama Valley - Lockwood Valley region, are offset to the San Gabriel fault zone to the Soledad basin, and in turn to the Orocopia region (Crowell, 1962; Bohannon, this volume). Others may yet be recognized in the Chocolate Mountain area east of the Salton Sea, a region now under study but incompletely known so far. During Pleistocene time, north-south shortening of the Transverse Ranges was severe, accompanied by basement-rock deformation, so that older foliations at places were markedly steepened and the strike today of these planar structures approximately parallels that of the range. Perhaps this same style of basement-rock deformation and uplift and tilting of blocks, coupled with deep erosion, accounts as well for the rough alignment of specific-gravity values and chemical isopleths. Deep erosion results in higher specific gravity and Ca, Mg, and Fe values exposed at the surface. Until we have similar chemical and density data over the whole region extending from the southern Salinia province and Sierra Nevada, to the region flanking the Salton Trough, it is difficult to appraise the significance of a limited band of data.

But even if we conclude that the Tejon, Soledad, and Orocopi terrains are disrupted parts of a once continuous terrain and hav been displaced about 300 km, (1 mi.) several perplexing proble still face us. It is not clear how large blocks have moved thr time, and especially in the regi between Cajon and San Gorgonio passes, nor how the San Gabriel fault zone joined the San Andreas in Pliocene time. The San Jacinto is a young branch of the system (Sharp, 1967), and it probably placed the Malibu-Cucamonga fault to the Banning fault (Baird, Morton, and others, 1974), but these events took place after jor right slip on the San Gabr fault zone. The through-going sys tem is pictured as predating th opening of the Gulf of Californ a and the Salton Trough.

Regional Tectonics

Near the Big Bend region of the San Andreas fault, in the nort central part of the Transverse Ranges, the San Gabriel fault n nected directly with the San An during Pliocene time and exten d northwestward through the Coas Ranges (Crowell, 1950). Begin n a few million years ago, and p bably directly following the o n ing of the Gulf of California the Salton Trough on the south Big Bend developed and the San Gabriel strand was abandoned. Th present main strand of the San Andreas fault, extending from the Big Bend to Cajon Pass along th south edge of the Mojave Deser and through the eastern San Gar Mountains, was strongly activa when the San Gabriel fault was abandoned. As the Big Bend de oped further, thrust faults bo to the north and south origina (1) On the north, the Pleito h ied mid-Tertiary strata across ly folded younger Cenozoic beds ath it, and (2) On the south the ier Mountain thrust system em- ed gneissic basement upon over- ed Plio-Pleistocene strata near e the San Gabriel fault is over- ed by these beds. In this re- , earthquakes, triangulation eys and level lines show that White Wolf fault is even more ve than the San Andreas fault , and in 1952 the Arvin-Tehach- and Bakersfield earthquakes rred on the White Wolf fault eshott, 1955). Structures in complex Big Bend region suggest a conjugate strain system is operating, in which there is gular north-south shortening, the history of the many faults as now understood suggests this conjugate system has only ated recently. The Big Pine and ock faults are now part of this ugate scheme, but in Pliocene they were separate and dis- t faults, and far from their ent positions (Crowell, 1962, 5). They have different his- es, were born far apart at erent times, and have probably recently joined the conjugate em.

orthwest of the Big Bend, the se and displacement of the San eas fault are well established ar as the post-late Miocene ory is concerned. Miocene es and volcanic rocks, laid across the future trace of the t, have been displaced a total bout 300 km (190 mi.) (Hall, ; Addicott, 1968; Huffman, 1972; nan and others, 1973). In fact, history and magnitude of this lacement on the north lends ort to the 300 km (190 mi.) of iar right slip in southern Cal- nia. On the north, however, may have been an earlier epi- of right slip of nearly the amount, bringing the total displacement on the San Andreas fault zone here to about 550 km (340 mi.). The fossil edge of continental crust, for example, where it met rocks characteristic of the ocean floor, is apparently offset from the Big Bend region to near Point Arena northwest of San Francisco (Hill and Dibblee, 1953; Ross, 1970). This earlier episode is possibly recorded also in late Cretaceous - Paleocene conglomerates, now found west of the fault in the Pt. Arena region. Stones within these conglomerates appear to be offset from their source area east of the fault now near the Big Bend region (Wentworth, 1968; Ross, 1972, 1973). Although there may be other ways to explain these relations, ways that do not involve the San Andreas fault as we now know it, many California geologists tentatively conclude that the San Andreas fault north of the Big Bend has had two major intervals of activity: (1) one late in Cretaceous or early in Paleocene times, and (2) another beginning late in Miocene times and continuing to the present (Suppe, 1970).

In southern California, however, this earlier period of movement on the San Andreas system, which might double the total displacement, has not been recognized. Recent field studies in the southwestern desert preclude the possibility of major strands existing to the east of the present San Andreas (Haxel and Dillon, 1973). On the other hand, faults to the west, such as those underlying the Newport-Inglewood zone, may have played this role at the times required (Suppe, 1970; Hill, 1971; Crowell, 1973; Howell and others, 1974). Such a possible fault along the Newport-Inglewood zone will now lie deep below the middle and late Tertiary infilling of the Los Angeles basin so that data pertaining to its early history is meagre (Hill, 1971; Yerkes and others, 1965, Yeats, 1973; Platt and Stuart, 1974). No acceptable scheme has yet been suggested to connect the San Andreas on the north to a deeply buried Newport-Inglewood fault on the south, or to any other southern fault, through the Transverse Ranges and across several major east-west trending fault zones, including the Malibu Coastal-Cucamonga system. We have therefore sidestepped this major problem, and have focussed attention on the San Andreas - San Gabriel - San Jacinto fault system to the east.

TECTONIC SUMMARY

The pliant crust of California is inexorably deforming across a broad and splintered belt where the Pacific lithospheric plate, moving relatively northwestward, meets the North American plate. In southern California at present, the San Andreas and San Jacinto faults are the principal discontinuities accommodating this relentless motion, as shown by earthquakes and measurements of crustal deformation and geomorphic evidence, but other subparallel faults to the east in the Mojave Desert and to the west across southern California and its subsea borderland are also active and somehow fit into the pattern. Major irregularities within this giant scheme result in squeezing to lift up the Transverse Ranges, stretching and sagging to form basins such as the Santa Barbara Channel and others offshore, and rifting to make the Salton Trough. Similar processes have doubtless operated in the geologic past across the region, but in addition, volcanism and plate-tectonic convergence and subduction have also taken place. The geologist's challenge is to work out the details of this historical panorama as far back into time as he can interpret data held within the the rocks. Moreover, only the cific geologic details of struc and lithology in relation to to raphy, have direct significance planning engineering works and human undertakings. Tectonic s theses are practically useful p marily in providing a predictiv guide to detailed investigation

In southern California, the Andreas fault system probably originated at the end of the Mi cene, or about 12 m.y. ago. Fo or 8 m.y., the San Gabriel faul zone was the principal strand o the system and probably joined San Andreas fault proper in the Cajon Pass - San Gorgonio Pass gion. From this complex region extended on southeastward into what is now the head of the Gul of California, where the record interpret its tectonic setting that time is at depth and obsc It is not yet clear whether the San Andreas was a transform fa at that time, but beginning ab 4 m.y. ago, it apparently pla a transform role in the openin the Gulf of California. As th Gulf opened, and Baja Californ and the Peninsular Ranges move relatively northwest, movement the San Andreas fault was vigo between San Gorgonio and Tejon passes, the San Gabriel strand abandoned, the San Jacinto fau became especially active as a subsidiary splay, and the Tran Ranges were sharply compressed uplifted.

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SEISMICITY ALONG THE SAN ANDREAS FAULT, SOUTHERN CALIFORNIA

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ABSTRACT

The San Andreas fault of central California becomes a complex system of parallel fault branches in southern California. The most seismically active branch south of the Transverse Ranges is the San Jacinto fault, although all branches show evidence of Holocene movements. In addition to the San Andreas fault itself, four principal zones of seismicity in the southern California region can be defined from the distribution of current seismicity: San Jacinto fault zone, eastern Sierra front, northern Baja California, Transverse Ranges. The five largest earthquakes of the past 130 years in southern California have occurred in diverse geologic and tectonic environments and in each of the seismicity zones except the San Jacinto fault. Strip maps show the instrumental epicenters along the San Andreas fault for a period of 41 years. Both the historical and instrumental records are unlikely to be statistically complete, especially as indicators of the near-future occurrence of larger earthquakes.

INTRODUCTION

Within the framework of plate tectonics, the San Andreas fault is a transform fault, the locus of relative, horizontal motion between the Pacific and North American plates. In northern and central California, the San Andreas fault in fact bears considerable resemblance to the textbook descriptions of narrow, linear plate boundaries along which relative displacements occur with little or no deformation interior to the adjacent plates. As was the case in the great San Francisco earthquake of 1906, this relative plate motion may take place in major but infrequent seismic events. Or in the case of the Bear Valley region of central California, the preponderance of relative motion may be effected in a more continuous, aseism manner. For long periods of time, relative displacements across certain fault elements simply do not occur, presently the case for the fault element broken by the 1906 earthquake. There seems little doubt, in view of the simplicity of this transform faul and a simple conservation of mass argument, that points along the San Andreas fault in central and northern California will all experience very nearly the same average rate of displacement and that the time interv required to obtain such an average is probably no more than several hundred years.

In southern California, however, the San Andreas fault exhibits considerab complexity. Amidst the great structu complications of the Transverse Range the San Andreas fault bends significa from its trend in central California and splays into a set of right-latera strike-slip elements. South of the Transverse Ranges, these elements include the Banning-Mission Creek, Sa Jacinto, Elsinore, and Newport-Inglewood faults and quite possibly one or more elements in the continental borderlands. The onshore members of this set, at least, have all been ac in the Holocene, and all are nearly parallel to the trend of the parent fault north of the Transverse Ranges They have not, however, been uniform seismic in the historic record.

Indeed, the geological, seismolog and structural complexities in south California are such that there is ev uncertainty which, if any, of these elements rightfully deserves the appellation San Andreas fault. Larg geological reasons, the term is rally reserved for the most easterly ch, the Banning-Mission Creek fault, een the eastern end of San Gorgonio and the Salton Sea. However, the t majority of seismic right-lateral, ke-slip motion between the Transverse es and the Gulf of California known he very short historic record has rred along the San Jacinto fault. he extent that the San Andreas fault be defined as the transform fault g which the plate motions occur, the Jacinto fault is the more legitimate mant to the parent name, at least at present time. In any case, it seems likely that a San Andreas fault se exists in southern California h of the Transverse Ranges than does n Andreas fault system.

ER EARTHQUAKES OF THE HISTORIC RD

igure 1 locates the larger earth-es which have occurred in the south- California region since 1890. The mic moment (M_O) of these earth-es are all in excess of 10^{25} dyne-cm. s a physical measure of the strength he earthquake, with a value equal to product $\mu\bar{u}A$ where $\bar{u}$ is the average lacement on the fault area A and μ he shear modulus of the source on. The seismic moment may be ob-ed from field observations of the ted surface or the elastic radiation ted by the earthquake. An empirical nique of estimating M_O from the l distribution of Intensity VI has described by Hanks and others 5). A significant advantage of M_O magnitude (M_L) as a measure of ce strength is that it provides a ct estimate of the relative seismic lacement for a specified fault ent through the cumulative sum of or earthquakes occurring along it. outhern California, earthquakes with 10^{25} dyne-cm always have local itude $M_L \geq 6.0$; but earthquakes with 6.0 do not always possess $M_O \geq 10^{25}$ -cm. Figure 2 displays the $M_L \geq 5$ seismicity of the region from 1932 through 1972.

The overwhelming contribution to right-lateral, strike-slip displacement known in the historic record of southern California arose in conjunction with the Fort Tejon (1857) earthquake. Displacements as large as 10 meters are inferred, and the total length of rupture extended along the San Andreas fault at least from Cajon Pass to a poorly defined point north of the Carrizo Plain (Wallace, 1968). In the twentieth century, this segment of the San Andreas fault, however, has been noticeably aseismic. Apart from it, Figures 1 and 2 define four principal seismic zones in the southern California region.

San Jacinto Fault Zone

Fifteen of the 36 earthquakes in Figure 1 have occurred along or can reasonably be associated with a seismic zone defined by the San Jacinto fault, sub-parallel fault elements in the Imperial Valley (Imperial, Superstition Hills, and Superstition Mountain faults) and the apparent extension of the San Jacinto fault from Cerro Prieto to the Gulf of California. This nearly straight, nearly continuous zone of seismic strain release has dominated right-lateral seismic slip south of the Transverse Ranges since at least 1890, geologic and tectonic details of local fault continuity notwithstanding.

Eastern Sierra Front

The Owens Valley (1872) and Walker Pass (1946) earthquakes have occurred along a northerly trending zone of seismic strain release paralleling the Sierra front. There is some suggestion in the earthquakes instrumentally recorded since 1932 that this seismic zone continues southwesterly along the Tehachapi mountains to their intersection with the San Andreas fault, thereby including the Kern County (1952)

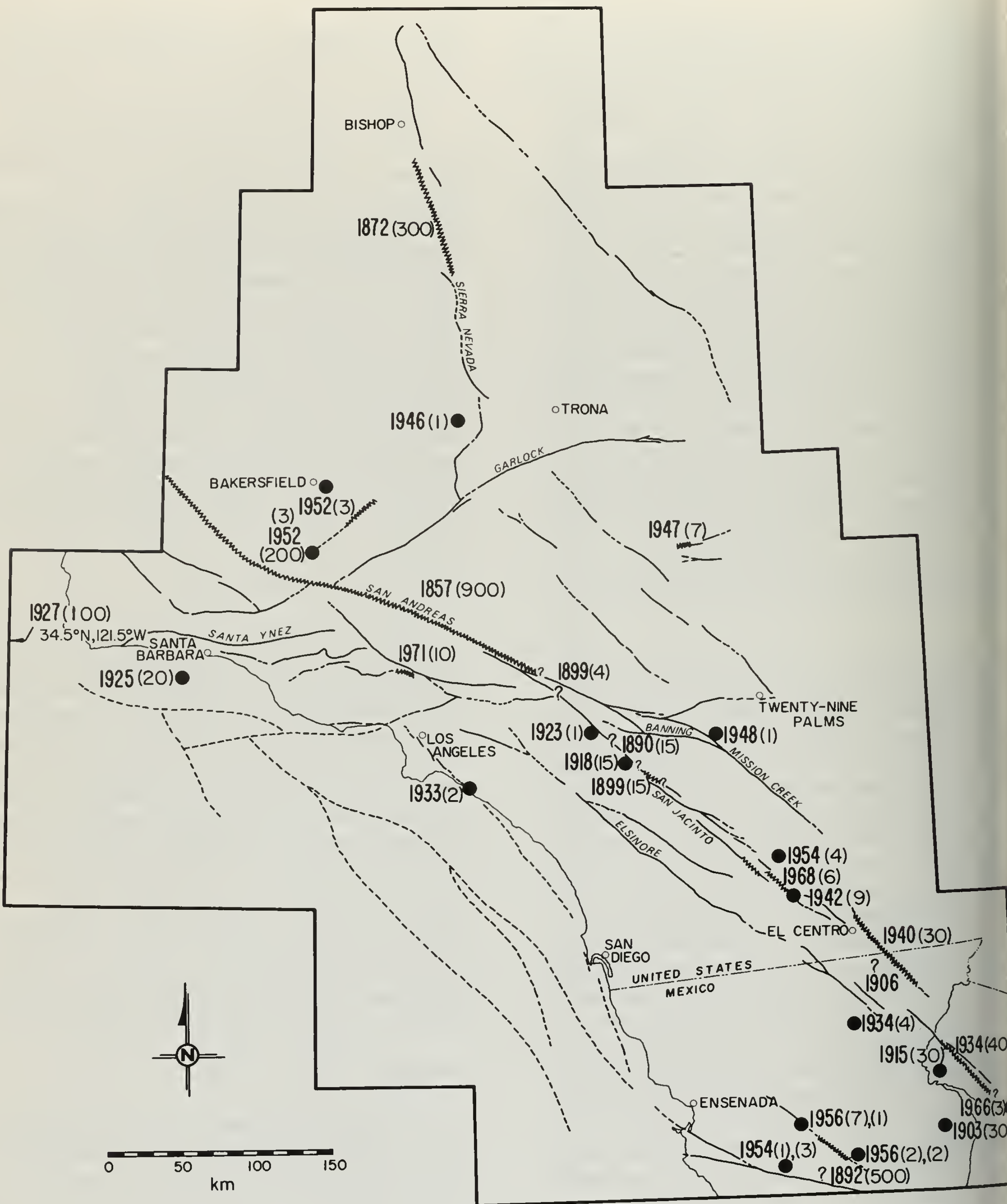
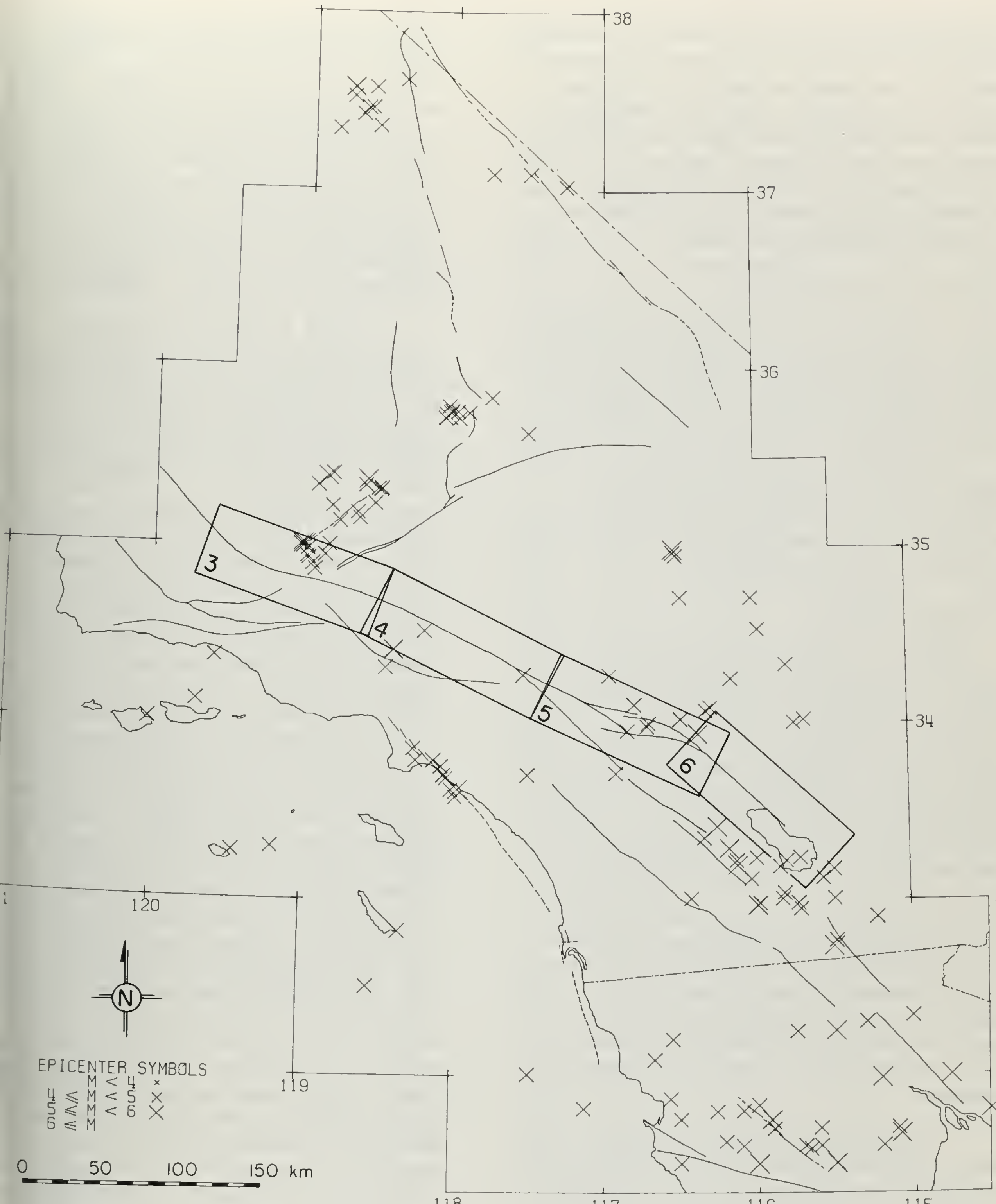


Figure 1. The larger earthquakes in the southern California region since 1857. All earthquakes shown have seismic moments (M_o) of 10^{25} dyne-cm or greater. M_o values are shown in parentheses in units of 10^{25} dyne-cm.



igure 2. All earthquakes of magnitude (M_L) 5.0 or greater in the southern Cali-
ia region, 1932 through 1972. Boxes show the areas enlarged in Figures 3 through 6.

earthquake and its aftershocks. Whether a zone of continuous tectonic deformation should be correlated with this larger zone is not clear, since earthquakes of both normal (1872) and reverse (1952) mechanisms have occurred along it. This zone is part of a more extensive zone defined by Ryall and others (1966) as the Ventura-Winnemucca zone.

Northern Baja California

The sequence of earthquakes in 1954, possibly on the Agua Blanca fault, and 1956 on the San Miguel fault in northwestern Baja California constitutes a major episode of seismic strain release in the southern California region. The large 1892 earthquake is inferred to be located in this region, but it is impossible to associate it directly with either of these two faults.

Transverse Ranges

A diffuse zone of seismicity occurs within the Transverse Ranges province from the Little San Bernardino mountains to beyond Point Arguello. This seismic zone, however, cannot be sharply defined, even with the instrumentally recorded seismicity since 1932. Large areas of the Transverse Ranges west of the San Andreas fault currently have only low seismicity. The occurrence of the December 12, 1812, earthquake, which strongly affected areas adjacent to the Santa Barbara Channel, and the possible association of the Point Arguello (1927) earthquake with the Transverse Ranges leave little doubt about the seismic potential of this province.

Of equal interest are those fault zones and tectonic elements that display geological evidence of tectonic deformation in the Holocene but which are currently nearly aseismic. Of these, the most striking is the Elsinore fault, which has not generated a $M_o \geq 10^{25}$ dyne-cm earthquake in this century. The current assessment of the seismic potential of the Newport-Inglewood fault primarily reflects the occurrence of the Long Beach (1933) earthquake and its aftershocks. Part of the San Andreas fault of interest in this volume, the Banning-Mission Creek fault southeast of San Gorgonio Pass is also relatively aseismic. In this century only one $M_o \geq 10^{25}$ dyne-cm earthquake has occurred along this fault, the Desert Hot Springs (1948) earthquake.

As noted by Allen and others (196 the available historic record of earthquake occurrence in southern California is not an adequate measure of the longer term spatial and temporal seismicity patterns of the recent past and, most probably, of the near future. Even in the four principal seismic zones discussed above, no $M_o \geq 10^{25}$ dyne-cm earthquake of the historic record is known to have affected the same fault area more than once, except in the course of an aftershock sequence. Long segments of otherwise active faults have experienced little if any seismic strain release. Of particular interest in this context are the diverse geologic and tectonic environments in which the five largest earthquakes of the past 130 years have occurred. These events are the Fort Tejon (1857), Owens Valley (1872), Baja California (1892), Point Arguello (1927), and Kern County (1952) earthquakes. Significant components of strike-slip, normal, and thrust faulting have been reported for the 1857, 1872, and 1952 shocks, respectively. While the precise locations and faulting mechanisms for the 1892 and 1927 earthquakes are unknown, it is clear that the spatial occurrence of the five earthquakes is not limited to any particular geologic province, mode of tectonic accommodation, or geographic locality. Perhaps more importantly, there is no reason to suspect that any such trend is presently developing or should be expected to develop on a time scale comparable to that of the available observations.

ICITY ALONG THE SAN ANDREAS FAULT

tailed strip maps showing the ibution of earthquake epicenters and near the San Andreas fault are given in Figures 3-6, and their ionships to the general southern ornia geography are indicated in e 2. In these maps, only a few of ore prominent faults are shown and are somewhat schematic, since their se is only to provide a frame of ence for the seismicity. The nters shown are those obtained by eismological Laboratory of the ornia Institute of Technology at ena using a network of seismographic ons in southern California.

e Southern California Seismographic rk has been improved many times its inception in 1927 with sponding improvements in the acy of epicenter locations. Most s since 1970 are located to about accuracy. For earlier events, the tainties may range from 5 to 15 km. arger earthquakes, $M_L \geq 5$ 1/2, and ally studied aftershocks, the tainties may be less than 5 km. tudies of seismicity, the location tainties of particular earthquakes e found in Hileman and others, (1974). to 1961, epicenters were determined aphical means and were reported to earest minute only, resulting in artificial north-south and east- alignments of epicenters which are cularly apparent in Figure 5.

r Earthquakes, $M_L \geq 5$

ble 1 lists all the earthquakes with 5.0 which have occurred within the s of the strip-map areas. Of these rthquakes, only 12 are close enough aces of the San Andreas system to st a direct relationship. Nine of 5 are associated with the 1952 Kern / earthquake and its aftershock Three are near the south end of alton Sea, and one is in the San rdino mountains.

Carrizo Plain to Lake Hughes (Figure 3)

Along the segment of the San Andreas fault shown in Figure 3, the strike of the fault changes nearly 35°, from about N43°W across the Carrizo Plains to about N78°W through fault-controlled Cuddy Valley. Such an abrupt angular change in a strike-slip fault certainly complicates the movements of rock masses in the vicinity of this bend. Although portions of the Big Pine, Garlock, and San Gabriel faults are shown here, the reader should refer to the geologic map accompanying this volume to appreciate the complexity of subsidiary faults near this change in the fault's trend.

The 1952 earthquake, $M = 7.7$, which ruptured the White Wolf fault and the associated aftershock series lasting more than 10 years accounts for most of the seismicity shown in Figure 3. The aftershock area was not aseismic prior to 1952, and Wesson and Ellsworth (1973) have pointed out that small earthquake activity before 1952 was higher in the epicentral area than in either the surrounding areas or along the nearby portions of the San Andreas fault. All of the $M_L \geq 5$ earthquakes in Figure 3 occurred in this aftershock series, with the exception of the southernmost epicenter which indicates an earthquake in 1941.

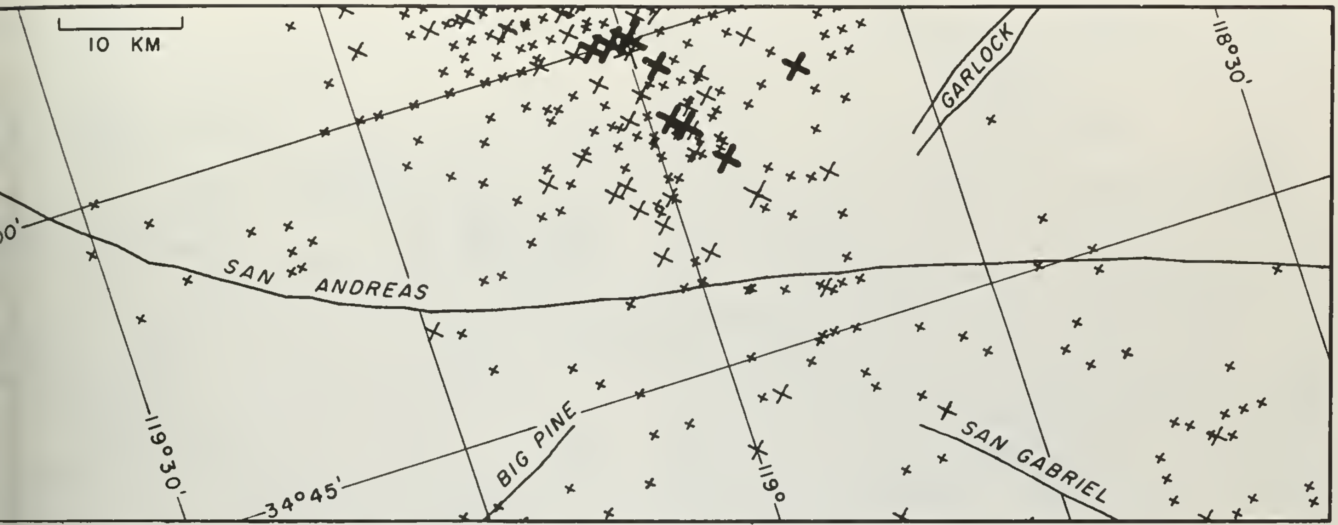
The few scattered, low-magnitude events along and near the San Andreas fault itself give little indication of the seismological significance of this portion of the fault. Even micro-earthquake activity as measured by Brune and Allen (1967) is very low here. The 1857 Fort Tejon earthquake ruptured this segment with an earthquake comparable to the 1906 San Francisco earthquake, all of the segment shown here being broken at that time. In 1916, an earthquake of approximately 5 - 5 1/2 magnitude occurred in the vicinity of Fort Tejon and apparently along the San Andreas fault.

Table 1

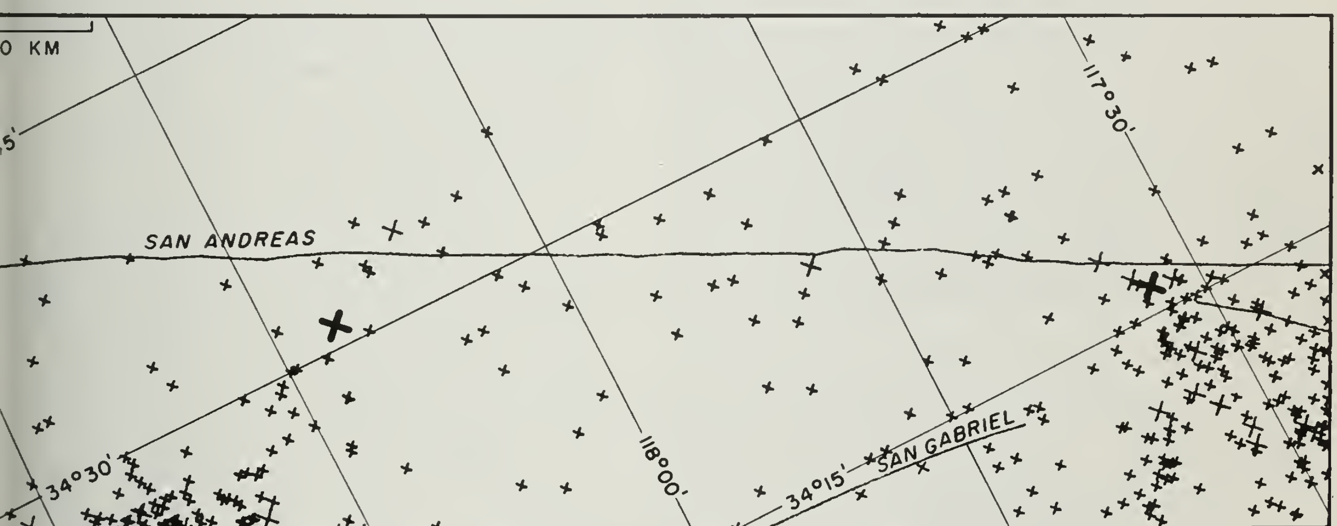
Earthquakes of $M_L \geq 5.0$ and Within the Strip Map Areas Shown in Figure 2

Date YY MM DD	Time HH:MM:SS	Lat.	Long.	Mag.	Quality
351024	14:48:07.6	34-06	116-48	5.1	A
410921	19:53:07.2	34-52	118-56	5.2	A
421022	01:50:38.0	33-14	115-43	5.5	C
430829	03:45:13.0	34-16	116-58	5.5	C
440612	10:45:34.7	33-58.6	116-43.2	5.1	A
440612	11:16:36.0	33-59.7	116-42.7	5.3	A
460928	07:19:09.0	33-57	116-51	5.0	B
470724	22:10:46.0	34-01	116-30	5.5	A
470725	00:46:31.0	34-01	116-30	5.0	C
470725	06:19:49.0	34-01	116-30	5.2	C
470726	02:49:41.0	34-01	116-30	5.1	C
481204	23:43:17.0	33-56	116-23	6.5	A
520721	11:52:14.0	35-00	119-01	7.7	A
520721	12:02:00.0	35-00	119-02	5.6	D
520721	12:05:31.0	35-00	119-00	6.4	D
570721	12:19:36.0	34-57	118-52	5.3	A
520801	13:04:30.0	34-54	118-57	5.1	A
520823	10:09:07.1	34-31.2	118-11.9	5.0	A
540112	23:33:49.0	35-00	119-01	5.9	A
540523	23:52:43.0	34-59	118-59	5.1	A
570425	21:57:38.7	33-13.0	115-48.5	5.2	B
570425	22:24:12.0	33-11	115-51	5.1	C
611115	05:38:55.5	34-56.5	118-59.2	5.0	B
630301	00:25:57.9	34-55.9	118-58.5	5.0	B
700912	14:30:53.0	34-16.2	117-32.4	5.4	A

Quality: A, B, C, D denote, respectively, < 5, 5, 15, > 15 km estimated location uncertainties



igure 3. Seismicity along the San Andreas fault, Carrizo Plain to Lake Hughes.



igure 4. Seismicity along the San Andreas fault, Lake Hughes to Cajon Pass.

EPICENTER SYMBOLS

$M < 4$	×
$4 \leq M < 5$	×
$5 \leq M < 6$	×
$6 \leq M$	×

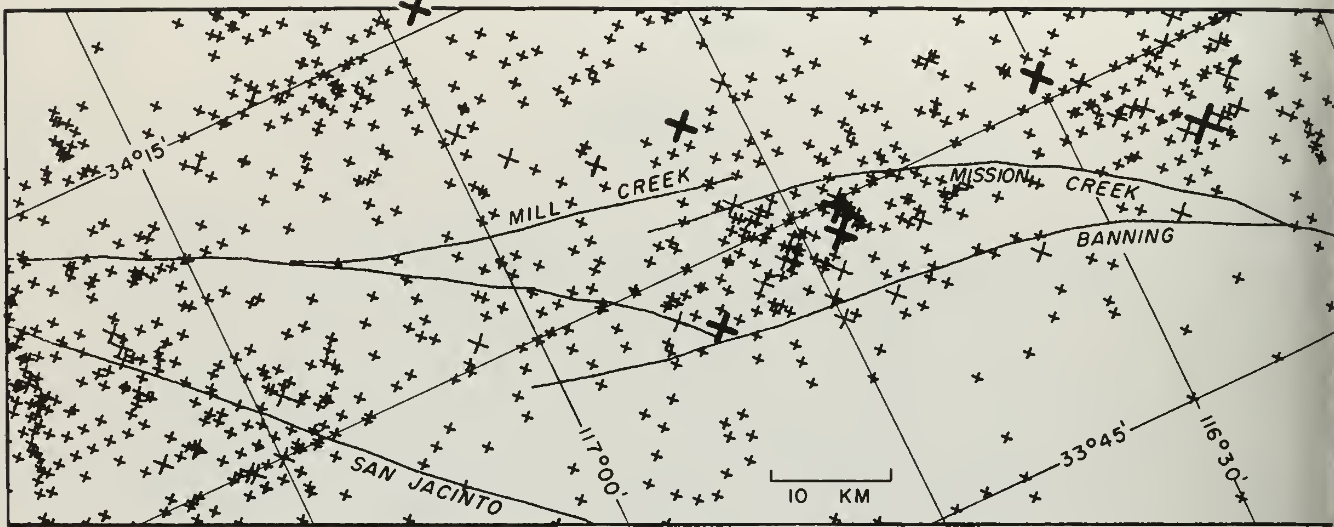


Figure 5. Seismicity along the San Andreas fault system, Cajon Pass to Desert Hot Springs.

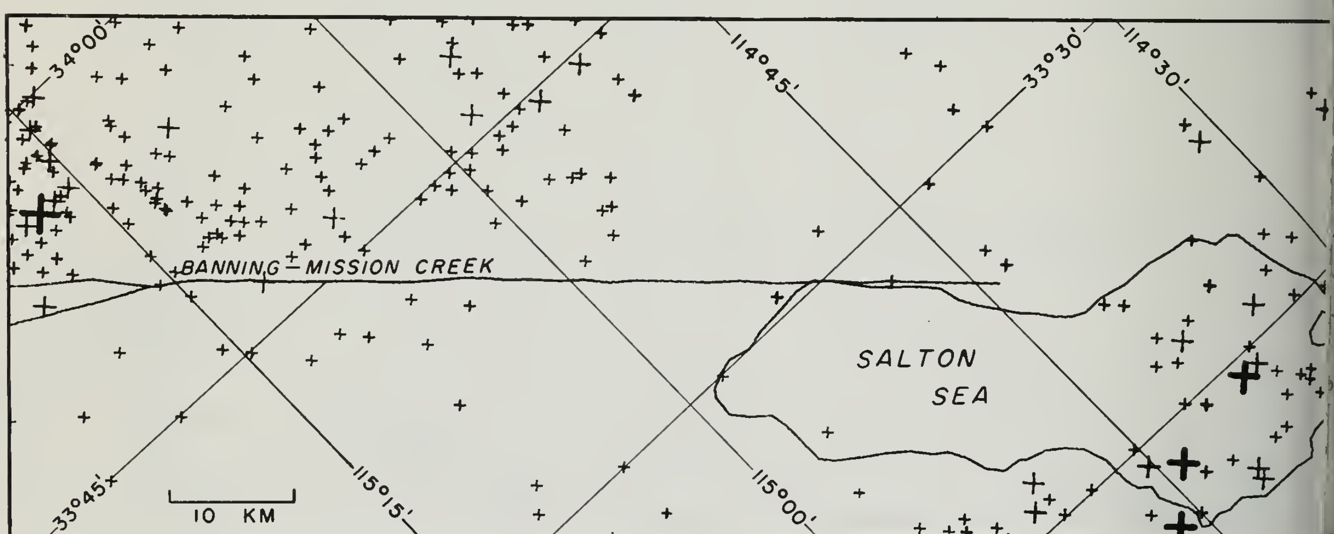


Figure 6. Seismicity along the San Andreas fault system, Desert Hot Springs to Salton Sea.

EPICENTER SYMBOLS

$M < 4$	×
$4 \leq M < 5$	X
$5 \leq M < 6$	**X**
$6 \leq M$	**X**

outh of the trace of the San Andreas t there is some rather diffuse micity that seems to persist through nearby parts of the Transverse Ranges, gh only a small portion is included . In the upper right corner of Figure s the westernmost portion of the ve desert, which is practically aseis- The left-lateral Garlock fault shows little seismicity as it nears the Andreas fault, but further to the heast, beyond this figure, there are l earthquakes near the trace.

Hughes to Cajon Pass (Figure 4)

he portion of the San Andreas fault n in Figure 4 forms the boundary een the San Gabriel mountains to the h and the Mojave desert to the north. two earthquakes of $M_L \geq 5$ have been rded instrumentally in this area, ough the 1857 earthquake did rupture or nearly all, of the San Andreas t shown. A M_L=5.0 earthquake occurred he San Gabriel mountains in August, , but the rupture was probably outside San Andreas zone itself, providing dip of the fault is near vertical . In September of 1970, a M_L=5.4 hquake occurred near the northern end he San Jacinto fault, where it ely approaches the San Andreas fault. cal mechanism solution for this k indicated thrust motion on a plane king nearly east-west and dipping to south (Carl Newton, unpub. data).

his particular local area where the Jacinto fault splays off from the San eas fault is the site of a fundamental ge in the characteristics of the San eas system. To the northwest, all the to Cape Mendocino, the San Andreas is ther well-defined fault zone seldom than a few km wide. And for 250 km he northwest, essentially the rupture he 1857 Fort Tejon earthquake, there currently only low levels of seis- ty along the fault itself. To the heast, the San Andreas system branches a number of parallel strands as dis- ed earlier. Seismic activity is moderately high to the southeast particularly along the San Jacinto branch, and these epicenters are evident at the right of Figure 4.

The activity shown in the lower right hand corner is part of the moderately high level of seismicity in the Fontana area. The concentration of epicenters near the lower left corner are the northernmost earthquakes of the aftershock series of the 1971 San Fernando earthquake. There is also rather diffuse activity throughout the San Gabriel mountains (south of the San Andreas fault) and in the eastern Mojave desert (upper right portion of the figure).

Cajon Pass to Desert Hot Springs (Figure 5)

Figure 5 shows the San Andreas fault system in the vicinity of San Gorgonio pass where the system comprises the San Andreas, Mill Creek, Mission Creek, and Banning faults. The San Jacinto fault splays off farther north near Cajon pass. For this area also, the reader should refer to the more detailed geologic map accompanying this volume, as well as Allen (1957), to appreciate the complexity of the fault relationships.

There have been no great historic earthquakes along this portion of the San Andreas system as there have been to the northwest in 1857 and 1906. The largest known earthquake along this portion of the system is the 1948 Desert Hot Springs earthquake with a magnitude of 6.5 - shown in the upper right of the figure. This earthquake probably occurred on the Mission Creek fault, since the aftershock zone was parallel to the fault and to the north of it, first motion studies constrain the motion to be a combination of thrusting and right-lateral motion, and surface exposures of the fault indicate about 62° dip to the northeast (Richter and others, 1958). Sixteen months earlier, in July 1947, and about 15 km northwest near Morongo valley, a series of earthquakes occurred which were apparently also on the Mission Creek fault. The largest earthquake was M_L=5.5, but three others of $M_L \geq 5$ also occurred so that this sequence was more like a swarm of earthquakes than a mainshock followed by smaller and smaller aftershocks. Two closely spaced earthquakes with magnitudes 5.1 and 5.3 occurred within a half hour on June 12, 1944, in the area between the Mission Creek and Banning faults. Dehlinger (1952) concluded that these consisted primarily of thrusting motion. Two other $M_L \geq 5$ earthquakes are close to faults of the San Andreas system, but their fault relationships are not clear - one, 1946, is near the intersection of the traces of the San Andreas and Banning faults and the other, 1935, is north of the Mill Creek fault near San Gorgonio mountain. A M_L=5.5 earthquake in 1943 is shown at the top edge of Figure 5; this is in the Big Bear Lake area and is not directly associated with the San Andreas system.

Smaller earthquakes are numerous in the area shown in Figure 5. Concentrations of activity are present along the San Jacinto fault zone (lower left), between the Mission Creek and Banning faults (center), and in the vicinity of the Desert Hot Springs and Morongo valley earthquakes (upper right). These concentrations, as well as the more widely scattered activity along the faults, reflect complex structural processes in this zone where relative displacement is being accommodated on many splaying branches of the fault system. Activity in the upper left of the figure is occurring within the San Bernardino mountains and relates only indirectly to the San Andreas fault zone.

Desert Hot Springs to Salton Sea (Figure 6)

Figure 6 shows the southern extent of the trace of the Banning-Mission Creek branch of the San Andreas fault zone. This branch has traditionally been considered as the "San Andreas" fault, although the San Jacinto fault, not sw in the figure, is the current locus o most of the seismic slip south of the Transverse Ranges. It is generally agreed that the Banning-Mission Creek fault continues on trend farther sout east, concealed under recent alluvium but the active segment probably stops near the south end of the Salton Sea.

The only large events shown in Fig e 6 are the 1948 Desert Hot Springs ear- quake at the left which was discussed above, and three events in the activi at the south end of the Salton Sea in 1942 and 1957. The 1942 event, M_L=5. near the center of the lake, occurred only 9 1/2 hours after a M_L=6.5 earth quake 40 km to the southwest. The tw events near the edge of the lake, M_L=.2 5.1, occurred within a half hour in 157

Very little current seismicity is evident along this portion of the Barin -Mission Creek fault. In 1968, apprci- mately one cm of fresh offset was ob- served near the north end of the Saltı Sea shortly after the Borrego Mountai earthquake occurred on the San Jacint fault (Allen and others, 1972) 70 km the southwest. The epicenters near e south end of the Salton Sea are part f the generally high level of activity n the Imperial valley. This activity now being studied in detail using a c network operated cooperatively by the California Institute of Technology a U.S. Geological Survey. The concent- tion of epicenters northeast of the Banning-Mission Creek fault is in th Little San Bernardino mountains and indirectly related to the San Andrea system as are the other elements of e Transverse Ranges.

ACKNOWLEDGMENTS

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ENGINEERING GEOLOGY AND THE SAN ANDREAS FAULT

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California Division of Mines and Geology

The effects of recent earthquakes in the United States, such as the San Fernando earthquake of 1971 and earthquakes elsewhere in the world, have kindled great interest and in some cases great horror and imagination. As an example, in 1969, emotional and irrational philosophies and "doomsday" predictions of a great earthquake lead to the concern, in some circles, that California would slip into the Pacific Ocean. During 1968 and 1969 prior to this "doomsday" event--that was to occur during the Easter week of 1969--many people in California prepared for this "doomsday" event in a variety of ways, and some even moved out of the State. This fear, based on misunderstanding, prevailed to the extent that even the news media were constantly reporting the predicted demise of California, contributing to the alarm felt by many people. Reports emerged saying that Howard Hughes had purchased land in Nevada because that State was going to become the shoreline, or beach area, or the Pacific. This fear probably resulted in part from Hollywood's renditions of the 1906 San Francisco earthquake and other great disasters, and the B.B.C. television program about earthquakes in combination with recent cultural developments dealing with psychic and astrological phenomena.

The predictions were appalling to those of us in science who believe that such a disaster is impossible. But even more appalling was the fact that people could become so hysterical over a fear that was so completely unsupported scientifically. Those of us trained in geology, seismology, and physics were aware of the fallacy of this doomsday prediction, but found it difficult to convince many students and others. It was also difficult to convince those who left California that Idaho, Montana, and Utah could also undergo severe earthquakes. On the other hand, aside from 1968-69 (doomsday predictions after the Santa Rosa earthquake), and immediately after the 1971 earthquake (San Fernando), it has been very diffu[lt] to convince the public, the politicia[ns], the press, and the students that eart[h]quakes will occur in California to an[y] extent that we should properly plan f[or] these events. It is often difficult [to] convince public administrators, elect[ed] officials, the news media, academia, [non-]geologist citizens, and even some geologists, that earthquakes will occ[ur] with sufficient frequency and intensi[ty to] be of concern. Fortunately, some do[es], with the result that codes, regulatio[ns], and procedures have been developed an[d] improved over the last half-century.

Most of the development and improveme[nt] of codes and regulations have been ke[yed] to catastrophes such as the Long Beac[h] earthquake of 1933, the Alaska earthquak[e] of 1964, and the San Fernando earthquake of 1971. Earthquakes in other areas [of] the world have also provided data to [a]ss[ist] engineers and geologists in better under[-] standing the causes and effects of earth[-] quakes. The articles related to legisla[-] tion in the January and February 197[5] issues of CALIFORNIA GEOLOGY, Californi[a] Division of Mines and Geology Specia[l] Publication 45, "Meeting the Earthqua[ke] Challenge," and the article by Slosso[n and] Hauge in the 1973 Association of Engineer[-] ing Geologists Special Publication, [illus-] trate some of the patterns of interes[t in] legislation related to seismic safety.

The February 1975 issue of CALIFORN[IA] GEOLOGY points out the relationship [be]tw[een] the number of earthquake and seismic[ally] related legislative bills introduced [and] those passed between 1968 and 1974. [T]h[e] analysis clearly shows that public i[nterest] immediately following a disaster has [an] effective control over legislation. [T]h[is] pattern is analogous to public reque[sts for] a traffic stop sign or signal follow[in]g serious auto accident. Another very important message in the February ar[ti]c[le] is that the emotional impact after a[...]

r often generates an over-reaction n produces legislation that may or may be beneficial and effective.

Geologists should keep concepts and res related to earthquakes and seismic ty within perspective and attempt at times to equate all of the hazards and lems in proper context. A recent oductory geology text indicated that people in the United States have taken talistic view about earthquakes. This of discussion is generally detrimental cientific and engineering progress. pite of some views, one has only to e the losses within the United States osses in other countries (with the ption, possibly, of recent earthquakes apan) to learn that even with some t comings in building codes and in gnition of geologic hazards, the ed States still has a very good record ted to damage and loss of life from nquakes. It is estimated that less 2000 lives have been lost due to nquakes in the United States in the 200 years. This loss when compared he great death toll from single nquakes that have occurred in such s as Peru, Agadir, Pakistan, Turkey, zuela, China, and Japan, reveals the ctiveness of earthquake codes and ations in this country.

oss of life from other hazards should be considered when discussing earth- e risks. As an example, the one year of life resulting from murders in Angeles County in 1974 was over 1600, y equal to the number killed by nquakes in the United States during past 200 years. Other examples, which d be equated when considering risk, the approximately 4500 lives lost in year as a result of motorcycle dents or the approximately 60,000 s lost each year from auto accidents-- at least 1/3 attributed to drunk ers. In addition, deaths in the ed States from natural hazards such as cane, tornado, flood, and fire far ed the deaths caused by earthquakes. ver, we must diligently pursue seismic ty.

It is significant that most seismologists, as well as the public, are concerned about the next magnitude 8± earthquake along the San Andreas. Those involved in seismic safety and/or earthquake engineering know that there is a need for better basic knowledge, better technology, and better codes. The research being conducted by the Earthquake Engineering Research Institute, the applied technology phase of the National Science Foundation Program, the California Institute of Technology, the campuses of the University of California at Berkeley, Los Angeles, Riverside, San Diego, Santa Barbara, and Santa Cruz, Stanford University, and the University of Southern California is improving the "state of the art" in earthquake engineering, applied seismology, and engineering geology. This Special Report, a joint effort by the Cordilleran Section of the Geological Society of America and the California Division of Mines and Geology to emphasize this problem, is an excellent example of people with various scientific interests pooling their information and working towards a better understanding of earthquakes and seismic safety.

The presence of the San Andreas fault, as well as other "active" faults in California, is the reason that California is called "earthquake country," and we can be sure that there will be damaging earthquakes in the future. The San Andreas fault sustem traverses both the San Francisco Bay region and the Los Angeles-Southern California region where 58 percent of the State's population of 20 million people live. A person living in California should expect to experience at least 3 moderate earthquakes approximately as large as the Long Beach, Bakersfield, San Fernando, or Santa Rosa quakes during his lifetime, and possibly one major earthquake the size of the San Francisco, Fort Tejon or Owens Valley quakes (Slosson, lecture, USC 1974). In order to survive such earthquakes and reduce losses, we must understand the earthquake-causing mechanism; the geographic location of the major active faults; the energy release on earth materials (such as liquefaction, landsliding, soil collapse and rock fall); and the effects of earthquakes on engineered structures.

The real and difficult challenge is that of being able to understand the cause and effect of earthquakes and then to convey this knowledge and information to the engineer and architect in understandable terminology so that he can implement safe and proper design. The engineer and architect must be presented with this information in a straightforward and, whenever possible, quantitative manner. It is then the engineer's or architect's responsibility to design the structure, whether it is a high rise building, hospital, school, power plant, or dam, for the site's geologic conditions so the structure can resist the anticipated seismic conditions. The very apparent need is for the geologist/seismologist to form a cooperative or "team" effort with the engineers and architects to develop a better understanding of the causes and effects and in turn to work toward the optimum in land use planning and design.

It is important that the geologist/seismologist retain a clear perspective of the problem being analyzed and provide the data that the engineers need. The geologist must not become emotional about earthquakes and oblivious to the other many natural hazards. The geologist must also refrain from placing financial organizational gains above public safety as eloquently described by Mason Hill in CALIFORNIA GEOLOGY, December 1974, "Role of Geologists in Evaluating Seismic Risks". An example of the basic content of a geologic/seismic report was presented by Perry Amimoto in his article entitled "Review of New Hospital Sites for Seismic Safety" (May 1974, CALIFORNIA GEOLOGY). This article was specifically prepared with reference to geologic/seismic reports for hospitals.

The San Andreas fault presents a difficult challenge to geologists and seismologists, because it can be assumed that urban development and construction will continue in land areas affected by the San Andreas fault system.

The incorporation of geologic/seismic knowledge into the preparation of land-use plans and the design of engineered structures is long overdue as can be demonstrated by many examples of improper or poor design and/or planning. All of us have viewed schools, hospitals, major buildings, fire stations, and other important or critical structures on the traces of active or potentially active faults or on adjacent earth materials that will produce adverse effects, such as liquefaction or landsliding, during an earthquake. Examples of such errors can be viewed while following the guide (such as this Special Report) published for the field trips of the 1975 Geological Society of America Cordilleran Section annual meeting. Some good examples of these are the Devore Elementary School, the fire stations along the San Andreas fault in the Wrightwood area and Leona Valley, the Interstate 10 and 15 interchange bridges near San Bernardino, as well as nearby hotels and schools, restaurants and motels at Gorman, and many others.

Luckily, urban development along and immediately adjacent to the San Andreas fault in Southern California has not been intense. However, urban sprawl is pushing towards the San Andreas fault and other active faults in Southern California, and economic and social pressures are apparent for the development of areas where seismic hazards can be critical. More intense development along the San Andreas fault and other dangerous faults has already occurred in the San Francisco Bay area. Noteworthy reference to this condition and related problems has been made in U.S. Geological Survey Circular 690 entitled, "Seismic Hazards and Land-Use Planning," and Circular 701 entitled "Goals, Strategy, and Tasks of the Earthquake Hazard Reduction Program." Both of these circulars should be required reading for every practicing or academic geologist involved in geology/seismology related to seismic safety. The trend of legislation and public opinion is such that geologists and seismologists now have the opportunity to be a part of the "team" and contribute to the processes of land-use planning and design of engineered structures.

ecent legislation in California has
red the input of geologic and seismo-
data. Assembly Bill Number 2300 in
nandated the use of the Uniform
ng Code. More recent legislation
g with changes in the California
strative Code have mandated that all
ons of the Uniform Building Code,
ding Chapters 23, 26, 29, and 70,
e adopted and enforced by cities and
es. Additional examples of bills
all for the implementation of-up-to
echniques by professional geologists
eismologists are SB 351 (1971) which
es that all cities and counties
e a Seismic Safety Element and a
ic Safety Element within their
l Plan; SB 479 (1971) and SB 689
requires that geologic analysis of
sites be prepared, SB 519 (1972)
es the preparation of geologic/
c reports for all hospital sites
ay 1974 CALIFORNIA GEOLOGY); and
(1972) requires the preparation of
ic reports for building sites within
l Studies Zones bounding designated
faults (see January, February,
r and December 1974 CALIFORNIA
Y).

ese legislative mandates have hope-
awakened Californians to the State's
resent seismic hazards and generally
alerted geologists and seismologists
ir professional responsibilities.
sional geologists and seismologists
keep these responsiblities, obliga-
, and liabilities in proper perspec-
nd recognize that there are, in
ion, other hazards, other dangers,
ther worries that concern the public.
chnical data, conclusions, and
endations must be presented to
rs, engineers, architects, public
ials, the public, and the press in a
that can be easily understood by the
ologist. Geologists must be accurate,
gh, and lucid in their reports and
all up-to-date in their presentation
plication of geologic knowledge and
It is recommended that all
ists and seismologists preparing
reviewing geologic/seismic reports
smic safety reports acquaint them-
selves with CDMG Note #37, "Guidelines for Geologic/Seismic Reports," Map Sheet 23, "Maximum Credible Rock Acceleration Map," and Preliminary Report 13, State of California, Preliminary Fault and Geologic Map."

In conclusion there are some very interesting philosophical issues that, warrent re-consideration and re-analysis if we are to solve the many problems related to earthquakes, fault activity, and seismic safety. Some of these questionable assumptions are;

1. The authoritative assumption that the Newport-Inglewood fault or its branches will not rupture to the surface (or produce surface rupture);
2. A fault will always rupture where it ruptured last--even though there may be a wide fault zone.
3. The method of field mapping that has been taught by some colleges and universities that you should not map a fault unless you and others can confirm displacement.
4. Earthquake magnitudes can be accurately predicted by measuring the length of the fault and then utilizing the formula $^{L}/2$.

These items, I believe, have allowed or caused some investigators to assume or infer geologic/seismic conditions about a site without adequate analysis. Such inadequate analysis has led, in some cases, to erroneous conclusions and recommendations.

Education is to get you where you can start to learn. --George Aiken

THE CALIFORNIA STATE WATER PROJECT AND THE SAN ANDREAS FAULT

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ABSTRACT

The earthquake engineering program conducted in connection with this project included special studies of San Andreas fault leading to (1) the selection of a route for the California Aqueduct which crosses this and other active faults at or near ground surface and (2) the adoption of aseismic design criteria which are considerably more conservative than those used for any previous water project.

Studies were undertaken to develop a better understanding of San Andreas fault, its habits, displacements, and the ground motions generated during its earthquakes. Sixty-five accelerographs were placed on and near select facilities to record future strong shocks; a network of sensitive seismographs was established to alert operations personnel immediately of earthquakes occurring at or near critical structures; tectonic deformations were and continue to be monitored to investigate possible adverse effects on the low gradient of the aqueduct and on the bearings of major pumping units; and special instruments including tiltmeters, pore pressure and stress cells, and force-balance accelerometers were installed at facilities that are located in exceptionally seismically active areas.

In addition to its contribution to the planning and design of this project, the earthquake engineering program is expected to yield records during future strong earthquakes which will a vance the state-of-the-art of earthquake engineering in gener leading in particular to improv techniques for the design of fa cilities for water projects.

INTRODUCTION

The State Water Project of California consists of a comple of reservoirs and aqueducts for the purpose of capturing and storing surplus stream flow in Northern California and conveyi it to areas of deficient water supply. Construction of the initial facilities has included 20 reservoirs, 5 power plants, 16 pumping plants, and 1,100 km of aqueduct.

Major elements of the projec consist of the 235 meter high Oroville Dam (the highest in th United States); A.D. Edmonston Pumping Plant (which boosts mo water higher than any plant in the world); and Edward Hyatt underground generating faciliti (one of the largest in the nation). The project is near com pletion. Its total cost will to about $3 billion. Almost 9 percent of this expenditure wi be reimbursed to bond holders through revenues from future w and power sales.

During the peak period of planning and construction, 134 earth scientists were employed i cluding 128 engineering geologists, 2 geophysicists, 2 seis ogists, and 2 geochemists. Ov a period of 21 years, the staf investigated dam and reservoir sites; routes for canals, pipe

, and tunnels; and foundations ower plants and pumping sta- . Much of this effort was ted to the study of earth- problems related to San as fault. Shown on Figure 1 e State Water Project and the active faults with which it contend. Also shown are areas tential land subsidence which red special treatment in con- ting the aqueduct. The effect future severe earthquakes will on these areas is not yet .

the early stages of project ing, the field of earthquake eering was in its infancy. At time, only six severe earth- s had been recorded by g-motion seismographs; and, quently, the nature of the d motions occurring near the e of an earthquake were y understood. Furthermore, ustomary practice of basing esign of hydraulic structures pseudostatic seismic factor ally on the order of 0.05 to was recognized as highly ical and in some instances ionable. In view of these comings, the California tment of Water Resources met representatives of the quake Engineering Research tute, a nonprofit organiza- dedicated to the improvement rthquake design. On recom- tion of that group, a 5-man lting board for earthquake sis was created, consisting cognized authorities in the of geology, seismology, soil nics, foundation engineering, tructural engineering.

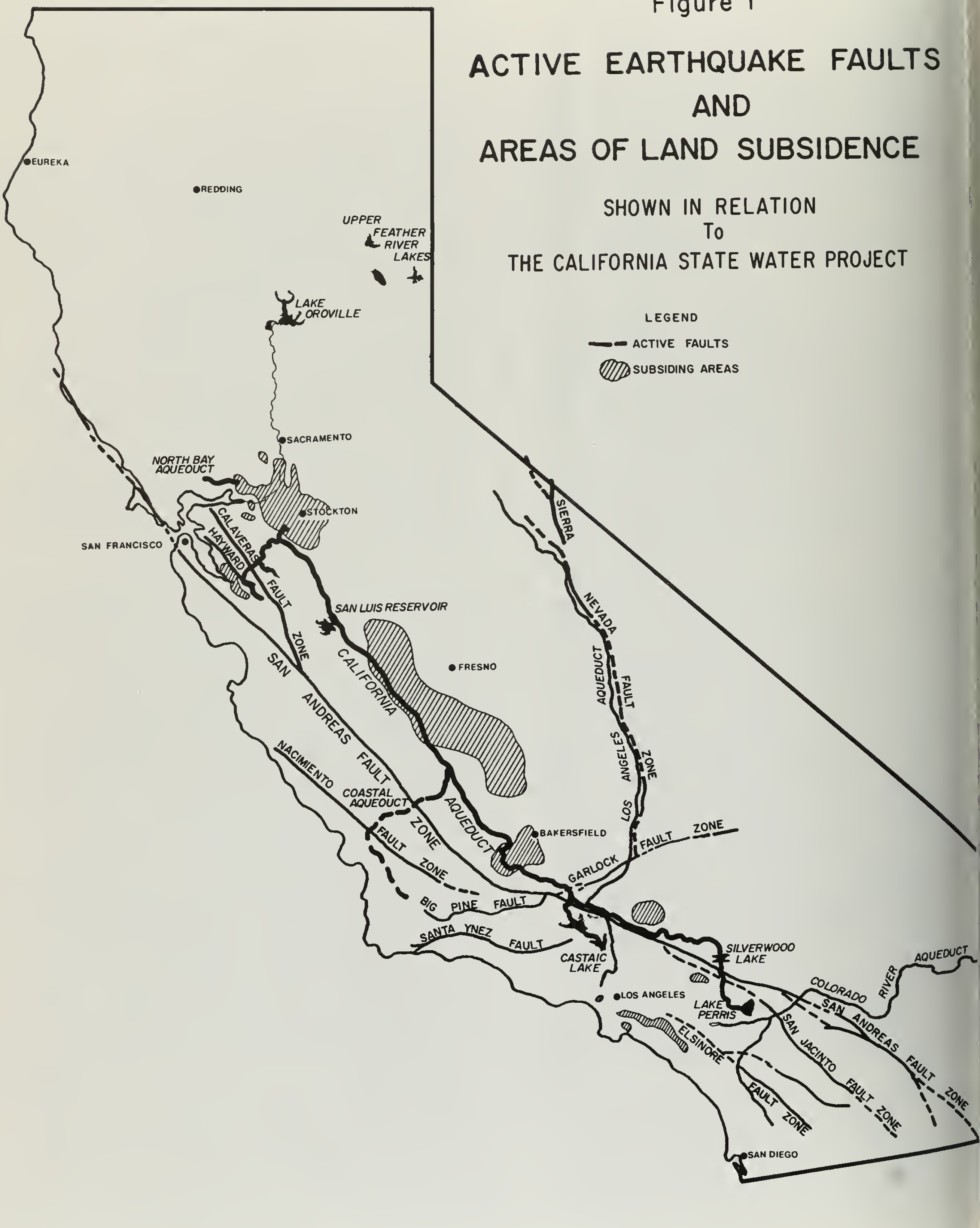
ofessor Hugo Benioff, seis- ist, served as the Board's chairman and upon his death ssor Clarence R. Allen, geol- , assumed this role. The recommended the establishment of an Earthquake Engineering Section to implement needed earthquake-related research and studies. This office was created; and, at the height of project construction, it employed four engineering geologists, two seismologists, one civil engineer, and six electronic technicians. The efforts of this group were devoted largely to studying the habits of the San Andreas fault; developing design earthquakes for planning and design purposes; and the installation and operation of an alerting system to locate with seismographs the epicenters of earthquakes throughout the State, measure their magnitudes, and, in the case of severe earthquakes, assure rapid dispersal of repair crews. The alerting system covers the water project and also 1,100 dams which come under the State's jurisdiction for safety.

The historic earthquake on San Andreas fault in 1857 is noteworthy because of its impact on planning the Project. This earthquake was centered in Southern California, and it occurred during the early settling of the State when most of the region was only sparsely inhabited. Nevertheless, the shock caused considerable disturbance and was felt throughout the Southwestern United States. Newspaper accounts reported landslides, uprooted trees, damage to the old Spanish missions, and reversal in the direction of stream flow in some areas. The ground surface along the trace of the fault may have ruptured over a length of 320 km. Inspections of offset stream channels indicate that the displacement was in a right lateral sense with a maximum on the order of 9 m. Although the seismograph had not yet been invented, it is generally believed that this shock exceeded 8.0 on the Richter magnitude scale. Some geologists contend

Figure 1

ACTIVE EARTHQUAKE FAULTS AND AREAS OF LAND SUBSIDENCE

SHOWN IN RELATION
To
THE CALIFORNIA STATE WATER PROJECT



it was the strongest experi-
d in California since civili-
on of the State. The recur-
e of a similar earthquake
y could disrupt all aqueducts
ying water to Los Angeles
e they cross the San Andreas
t. These include the
Angeles Department of Water
Power Owens Valley aqueduct
the Sierra Nevada, in service
e 1912, and the Colorado River
duct of the Metropolitan Water
rict of Southern California
leted in 1934. The Owens
ey aqueduct crosses the
Andreas fault 183 m below
nd surface in tunnel. The
rado River aqueduct makes
crossing in a pipeline.

Ground water comprises
oximately 40 percent of the
l annual dependable water
ly to Los Angeles. Experi-
has shown that this source
may be disrupted during
hquakes by shearing and
apse of well casings, damage
eep-well turbine pumps and
ruction of electrical
lities such as transmission
s, switchyard apparatus, and
transformers. The possibility
all water supply systems for
Angeles could be damaged by
vere earthquake emphasized the
rtance of: (1) locating the
duct to permit ready access
amaged facilities, (2)
rporating surplus storage in
inal reservoirs for use while
irs can be made, and (3)
tructing interconnections
een major aqueduct systems
aximize backup capability.

CTION OF THE AQUEDUCT ROUTE

A particularly important step
he early planning was the
ction of the route for the
duct through the Tehachapi
tains. This range lies south of the Great Valley of California and separates it from the Los Angeles Coastal Plain. Two basically different plans were proposed; both involved crossing the San Andreas fault, but each differed in the manner in which that crossing would be accomplished.

One of the alignments considered was known as the Long Tunnel Route or 1870 Tunnel, 1870 being the elevation of the crossing in feet above sea level. This route included a tunnel approximately 6 m in diameter and 43 km in length. It extended from the southernmost tip of the Great Valley to Castaic Reservoir, a terminal storage facility located north of Los Angeles. The long tunnel was aligned to pass beneath the Tehachapi Mountains with a maximum cover of 1,197 m. The San Andreas fault would be penetrated at a depth of 550 m. Four other major faults with questionable habits would also be intersected at depth.

The investigation of the long tunnel route was novel in that the entire study, including the selection of the alignment, construction scheduling, and preparation of the cost estimate for the tunnel and its three access shafts with hoists was undertaken exclusively by engineering geologists. It was estimated in 1954 that it would cost $227,000,000 to build this tunnel.

The principal alternative to the long tunnel route was known as the High Line or 3,360 Route, the numbers again reflecting tunnel elevation in feet above sea level. This route included a pumping station of unprecedented size to lift a flow of 116 cubic meters per second a height of 590 m. The pumps would deliver water to a series of four tunnels driven through the crest of the Tehachapi range, the longest of which would be 6.5 km. Selection of the alignment for these tunnels was based largely on geologic investigation. The route avoided crossing the San Andreas and other active faults at depth. Fault crossings were accomplished at ground surface where repairs to earthquake damage could be made rapidly. Beyond the ridge of the Tehachapi Mountains, the high line route bifurcated -- an east branch conveying water to the Mojave Desert, San Bernardino, and the eastern coastal plain and a west branch conveying water to Castaic Reservoir. Large amounts of electric power would be required for pumping, only a portion of which could be recovered at power plants located at the southern base of the range.

Early studies led to a decision favoring the high line route which has since been constructed and is now in operation. This decision was governed largely by geological factors, including earthquake hazards related to San Andreas fault and to the high cost of tunneling through fault zones at depth.

The California Aqueduct system, when completed in the 1980's, will cross the San Andreas or its tributary faults at nine points on the surface. In planning these crossings consideration has been given to minimizing down time during outages caused by earthquake. Two of these crossings are shown in Figures 2 and 3.

EARTHQUAKE ENGINEERING PROGRAM

The principal activity of the Department of Water Resources' Earthquake Engineering Section between 1959 and 1968 was its Geodimeter Program--- a program to measure gradual fault movemen that could disrupt the State Wat- Project. Fault or strain movement on the San Andreas and tributary faults was detected directly by measurement of chang in the distance between permanen monuments located on either side of the fault. A Model 2A geodimeter was used for this purpose. More than 3,000 kilometers of lines were measured annually. Along the San Andreas the averag annual right lateral movement wa determined to be about four centimeters near Hollister diminishing to no measurable movement near Los Angeles.

In 1962 the Department's Consulting Board for Earthquake Analysis recommended seismic design criteria to meet expecte ground shaking resulting from severe earthquakes. These crit were based on a San Andreas fau design earthquake which conside the strong-motion record obtain from the 1940 earthquake near El Centro, California, adjustin the resultant velocity and acceleration spectra of that sh to a maximum of 0.5 g horizonta and 0.33 g vertically. Followi the 1971 San Fernando earthquak the original criteria were upda taking into account hazard to human life, proximity to causit faults and frequency of occurre of earthquakes.

In 1963-64 the State, in cooperation with the USC&GS, began establishing small (150-500 meter) highly precise triangulation figures in the vicinity of aqueduct facilities which cross known active faults This type of triangulation figu has been referred to as a "Hollister type" or "fault movement quadrilateral". Both vertical and horizontal ground

Figure 2. In planning the California State Aqueduct, the State's practice was to cross active faults on or near ground surface to permit rapid repairs to facilities such as this siphon in the event of earthquake damage.

Gating at this siphon makes possible cut-off of the flow. A water level sensing element which responds to rapid changes in water surface elevation in the canal prism registers an alarm in an Area Control Center. The gate-closing mechanism can be remotely activated or operated locally.

Figure 3. The San Andreas fault near Devil Canyon power plant. The physiographic manifestations of the fault are evident near the foot of San Bernardino Mountains where its trace (marked by arrows) crosses the photo from left to right. A lateral offset of several feet may have occurred on this segment of the fault in 1857. The power plant was located upstream of the fault, thus avoiding the risk of rupturing high-pressure penstock by displacement during a future earthquake.

ments (creep) are measured
ne order of a few millimeters.
ty-one such figures were
blished on the San Andreas or
tributary faults from the Bay
to San Bernardino.

Critical structures and
lities of the California State
r Project have been instrumented
strong-motion accelerographs
ecord strong ground shaking
lting from earthquakes. The
is the acquisition of
rtant structural response data
evaluating the design of exist-
structures and for design of
e ones. Presently 65 strong-
on accelerographs are installed
ams, pumping and generating
ts, and at free field sites.
arrays of accelerometers
placed perpendicular to
ndreas fault to measure the
uation of strong motion with
nce from the fault. Addition-
force-balance accelerometers
embedded in several of the
ng plants and dams. Other
ic instrumentation in some
e dams includes stress and
pressure cells.

Installation of tiltmeters
key facilities was recommended
use of possible adverse effects
ectonic deformation on the low
ent of the aqueduct and later
use of concern over the
ble effect on the bearing
of the Project's large pumps.
een 1964 and 1966, seven, two-
onent continuously recording
meters were installed,
rily at pumping plants, and
within a few miles of the
ndreas fault. No significant
was observed during three
of operation. All tilt-
rs were dismantled in 1968.
effects of tilting on the
was not as critical as
thought and the most
ficant vertical movement
affecting the aqueduct has been
land subsidence which can be more
effectively monitored by leveling
surveys.

A statewide cooperative sensitive seismic network was established to monitor seismic activity (1) affecting facilities of the California State Water Project, particularly during filling of the reservoirs, and (2) to provide a round-the-clock notification for alerting maintenance personnel of earthquakes of magnitude 5 or greater occurring in vicinity of the facilities. Telemetry of these and other stations to Sacramento began in 1968. Through a cooperative telemetered exchange of seismic stations, establishment of a statewide network was completed in 1971. Presently 27 sensitive seismic stations including 10 operated by the State Department of Water Resources are telemetered to Sacramento and recorded. Cooperating agencies are the University of California at Berkeley, California Institute of Technology, the United States Geological Survey, and the University of Nevada.

The California Department of Water Resources has funded research at the University of California, Berkeley, Department of Civil Engineering, to improve seismic design criteria for dams and other structures. Studies have included dynamic analysis of earth dams, liquefaction of sands under cyclic loading conditions, lateral soil pressures on rigid structures, and cracking in earthfill dams as a consequence of shaking in various azimuths. Investigations presently underway will provide guidelines for analyzing dynamic behavior from real seismic data obtained at instrumented dams, towers and pumping plants following future earthquakes.

After the San Fernando earthquake of 1971, the Department funded studies of "Measurements of Dynamic Characteristics of Electrical Equipment" through Stanford University, Department of Civil Engineering. These measurements were made at pumping and generating plants along the southern portion of the California Aqueduct and adjacent to the San Andreas fault zone. Dynamic characteristics of various electrical switchyard equipment and associated structures were measured. For comparison the characteristics were also determined analytically. These and further studies will provide improved seismic design criteria and requirements for new and existing mechanical and electrical equipment and civil features. Facilities will be modified to increase their seismic resistance as indicated by the studies.

CONCLUSION

Planning, design, construction, and operation of the California State Water Project were based on the assumption that a great earthquake will be experienced on San Andreas fault during the life of the facilities. Consequently, dams, power plants, pumping stations, and related switchyards were located away from the fault zone to avoid rupture by offsetting. The principal structural elements of the project were designed to withstand the ground motions expected during a magnitude 8 earthquake. Although 65 strong motion accelerographs were deployed during the planning stages, no great earthquakes were recorded during this interval. Design earthquakes were therefore based on data from other regions with emphasis on ground motion recorded for the El Centro earthquake of 1940.

The aqueduct route, which unavoidably crosses the San Andrea, was located to pass over this an other active faults at or near ground surface. This precaution is expected to expedite repairs damage caused by faulting. As a added contingency, terminal rese-voirs were enlarged to provide extra storage while repairs to damaged facilities can be made.

The objective of the earthqua engineering program has been to build the California State Water Project stressing public safety, system reliability, and economy construction and to develop the state-of-the-art for future wate systems.

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Professor Clarence R. Allen, California Institute of Technol Pasadena, California.

CRUSTAL MOVEMENT INVESTIGATIONS ALONG THE SAN ANDREAS FAULT IN SOUTHERN CALIFORNIA

By John H. Bennett and Donald A. Rodgers
California Division of Mines and Geology

ACT

odetic investigations of crustal move- associated with the San Andreas fault en Cholame and the Imperial Valley the past forty years have shown no nce of fault slippage, and with the ble exception of the southern Imperial y, no clear indication of strain accu- ion has been detected. This lack of ved movement suggests that the fault e locked to a considerable depth. precludes surface observation of the n field from movements occurring at . In spite of the absence of percep- movement on the San Andreas fault, us indications of relatively short- deformational behavior and apparent nal uplift in the Transverse Ranges g the past decade testify to a dynamic onment.

DUCTION

odetic surveys conducted subsequent e 1906 San Francisco earthquake pro- the first insight into the magnitude real distribution of crustal movement iated with a major seismic event and ded the basis for Reid's classic ic rebound theory of earthquake gen- on. Additional resurveys during the 1920's provided conclusive evidence latively large continuing displace- associated with the San Andreas system. These results led to initia- of a geodetic program specifically ned to assess long-term crustal defor- n occurring on major faults in ornia.

ring the early 1930's, several arcs iangulation and traverse-leveling net- were established by the National Survey (then U.S. Coast and Geodetic) along the San Andreas fault in southern California. The resurveys of these networks -- conducted over a geologically brief 40-year period -- constitute the oldest source of geodetic data available for crustal movement studies in southern California other than portions of the national geodetic control network that have been fortuitously located in areas of interest. Observational errors inherent in this type of survey require an interval of 10 or more years between reobservations and necessitate the passage of 20-30 years before reliable conclusions regarding strain accumulation can be drawn.

The advent of electro-optical distance ranging instrumentation during the 1950's greatly enhanced the capability to determine geodetic distances. Accuracy was increased by an order of magnitude, and more frequent reobservations became practical. Concerned with the effects of fault movement on planned facilities of the State Water Project, the California Department of Water Resources (DWR) in 1959 initiated a measurement program utilizing this new instrumentation (Geodimeter). Periodic remeasurements were begun over a network of more than a hundred 15-30 km lines extending along the San Andreas and related faults from the San Francisco Bay region to Riverside County. This program has been continued by the California Division of Mines and Geology (CDMG) since 1968 and the United States Geological Survey (USGS) since 1971.

Through cost-sharing cooperative programs between DWR and the National Ocean Survey (NOS) during the period 1959-1968, reobservation and analysis of some of the older NOS networks were completed. Several new geodetic investigations were initiated in southern California including a large-scale regional triangulation network encompassing the major faults in the

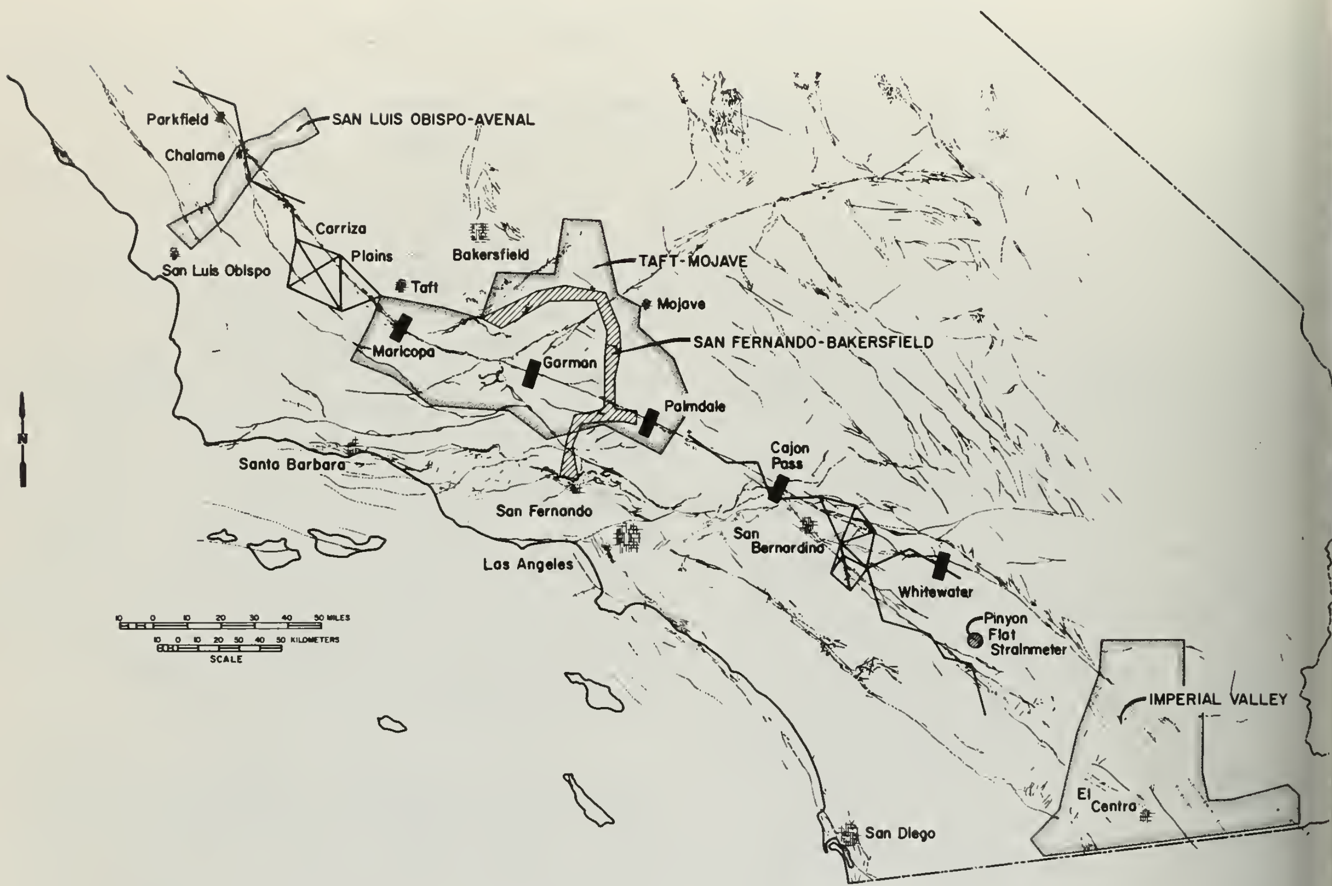

Figure 1. Locations of major geodetic crustal movement investigations along the San Andreas fault in southern California. Shaded areas indicate locations of triangulation networks and solid areas indicate locations of Traverse-leveling networks. Individual lines indicate selected portions of the Geodimeter network Holocene and historically active faults taken from Jennings (1973).

Tehachapi Mountains region, four additional arcs of fault zone triangulation, and 16 small survey figures (fault movement quadrilaterals) for monitoring fault creep. An extensive program of geodetic leveling was also undertaken during this period.

More recently, the USGS and the universities have become increasingly involved with crustal movement investigations. The USGS, notably, has significantly extended the coverage of the original Geodimeter network.

Results of the major geodetic investigations along the San Andreas fault in southern California are briefly summarized herein. Individual projects are described in geographical sequence along the fault beginning near Cholame in northern San Luis Obispo County and extending south to the Imperial Valley. Where a project is of a scope that it encompasses oth major faults, discussion in generally limited to the results associated wit San Andreas fault. The Geodimeter re are of a more regional nature and are cussed last. Each project summary is designated by the type of survey, the cation-designation and the agency(s) responsible.

Two recent references are particul noteworthy: (1) National Ocean Surve (1973) provides, in a single volume, of the reports of crustal movement i igations prepared by NOS during the

71; (2) Greensfelder (1972) reviews istory of crustal movement investons and lists locations, dates of llation, years and/or frequency of vations, responsible agencies, and uments employed in the measurement of al deformation throughout California. s a particular reference is cited n, reports of NOS investigations will und in National Ocean Survey (1973).

TS OF CRUSTAL MOVEMENT INVESTIGATIONS

scussion of the results of crustal ent studies along the San Andreas in southern California would not be ete without noting the type of moveoccurring along the San Andreas in the central Coast Ranges northof Cholame. Movement along this m segment of the fault occurs as slip or "creep". Actual displacein most areas seems to occur along a less than 6 meters wide (Raleigh and rd, 1969). Creep generally occurs mically, reaching a maximum rate of ximately 3 cm per year throughout of this fault segment. This rate is asonably good agreement with Geodi measurements and the average acement rates derived from longertriangulation data (Savage and rd, 1973), indicating that strain ulation is nominal along this section e San Andreas fault. The slip rate he level of seismic activity dimin near the extremities of this section. outhern limit of seismic activity easurable creep is near Cholame in ern San Luis Obispo County.

GULATION: SAN LUIS OBISPO TO ENAL (NOS)

is triangulation arc, extending ximately 120 km from the coast near uis Obispo northeast to the Kettleman , crosses the San Andreas fault near me. The arc was established in 1932 eobserved in 1951 and 1962. A al resurvey of those stations near an Andreas fault was completed shortly the magnitude 5.5 Parkfield earths of June 1966. A comparison of tic positions derived from the 1932 and 1951 surveys indicated right-lateral movement of approximately 15 cm between stations straddling the fault. It is not clear whether this movement represents displacement near the end of the fault break of the 1934 Parkfield earthquakes or whether it represents creep at a rate of approximately 8 mm per year. Observed changes between the 1951 and 1962 surveys were not significant, suggesting that the differences noted during the previous period were a consequence of the 1934 earthquakes. The post-earthquake observations in 1966 disclosed right-lateral movement of approximately 15 cm since the 1962 survey; this offset agrees with both Geodimeter measurements and observed surface rupture resulting from the 1966 earthquakes.

Southwest along this arc, significant displacements normal to the structural trend are indicated which suggest thrusting or compressional strain associated with subparallel northwest-trending faults. To further investigate the possibility of fault activity in this region, in 1974 CDMG initiated a program of annual Geodimeter measurements west of the San Andreas fault.

FAULT MOVEMENT QUADRILATERAL: "TEM" SITE (NOS/DWR)

This small survey figure, with dimensions on the order of 300 m was established in 1964 and reobserved in 1965; it straddles the San Andreas fault approximately 7 km southeast of Cholame. Reobservations following the 1966 earthquakes revealed right-lateral displacement of 2.5 cm, evidently a result of the earthquake. The 1971 resurvey indicated continued right-lateral displacement at an average rate of approximately 7-8 mm per year, which represents the effects of fault creep at or very near the surface. There is no evidence of fault creep south of this location.

TRAVERSE-LEVELING: VICINITY OF MARICOPA (NOS)

One of the survey programs initiated by NOS during the 1930's was the establishment of several traverse-leveling networks crossing major faults in southern California. These networks consist of a series of closely-spaced monuments (100'-500' spacing) crossing the fault near right angles and extending approximately 7-8 km on each side. Both horizontal positions and elevations are determined.

The network near Maricopa was established in 1938 and is located along State Highway 166, crossing the San Andreas fault at Camp Dix. Resurveys for horizontal movement in 1948 and 1959 and numerous relevelings have revealed no evidence of movement.

TRIANGULATION - "TAFT-MOJAVE" (NOS/DWR)

During 1959-60, a regional triangulation network was established in the Tehachapi Mountains by the U.S. Coast and Geodetic Survey and the California Department of Water Resources. As an integral part of this survey, many of the network lines were measured with the Geodimeter. During 1967-68, the entire net was re-observed. The following results are from the project report (Miller and others, 1969):

> "The resultant position vectors and their corresponding 95% confidence error ellipses show that the changes in position are within the limits of observation. However, significant patterns exist. Strain is more evident than fault slippage. There is an area of expansion east of the Garlock fault and north of the San Gabriel fault. The remainder of the net generally contracts or compresses. Along the White Wolf fault, the Geodimeter results show there is left-lateral movement of about 9 cm. for the interval 1959-60 to 1967. On the San Andreas fault, west of the junction with the Garlock and San Gabriel faults, the Geodimeter results indicate right-lateral movement of about 9 cm. for the 7-year period. Along the Garlock fault and the San Andreas fault east of the junction, the results indicate strain rather than slippage."

The establishment of this network resented a major step toward the stu crustal deformation in this complex However, several comments about the sults quoted are in order. First, t overall accuracy of the survey was a 4 parts per million. Thus the resul obtained are well within survey erro although the internal consisteny of results does give them greater credi Second, and perhaps more important, hypothesis of a time-variable strain advanced by Greensfelder and Bennett (1973) is valid, it may be difficult separate the effects of time-varying strains and tectonic strains. Addit resurveys will be necessary before m substantive conclusions are warrante

TRAVERSE-LEVELING: VICINITY OF GORM (NOS)

This network crosses the San Andr fault near Quail Lake approximately southeast of Gorman. Surveys for ontal movement were completed in 193 1949, and 1966; releveling has been plished on several occasions since 1 Results of all surveys indicate no m ment on the fault.

TRIANGULATION: SAN FERNANDO TO BAKE (NOS)

This narrow arc of triangula crossing the San Andreas fault betwe Lake Hughes and Palmdale, lies almos totally within the Taft-Mojave regio network. Established in 1932, the a was resurveyed in 1952-53 following Arvin-Tehachapi earthquake and agai 1963. Results of the three surveys the portion of the arc near the San fault show no evidence of fault move

PRECISE LEVELING: CENTRAL TRANSVERS RANGES (NOS)

Since 1960 the NOS, with consider support from DWR, has accomplished leveling along various routes in the Transverse Ranges. As a result of surveys, Meade and Small (1966) rep apparent recent uplift of several foot along the main north-south level between Los Angeles and Gorman. More ntly, Castle and others (1974) have zed these and other data, concluding a general uplift did occur over this on during the previous decade. In ion, localized uplift of an apparent-isodic nature is indicated south of lale and over the upper plate of the ernando fault prior to the 1971 quake. Near Palmdale, a maximum up-of 20 cm occurred during the period -64.

stle and others (1974) state "In of the limitations inherent in the ts presented here, these results cate clearly and unequivocally that central Transverse Ranges have under-extensive tectonic uplift during the decade. The uplift, however, has proceeding irregularly in both space ime; whether these irregularities are ions chiefly of the chaotic nature of crust in the area (see Jennings and d, 1969), or are somehow related to tions in primary tectonic drive rates, early an open question."

RSE-LEVELING: VICINITY OF PALMDALE OS)

itial observations of this network completed in 1938 and repeated in and 1958. These data and the results veral relevelings have produced no nce of fault movement.

MOVEMENT QUADRILATERALS: TEJON PASS CAJON PASS (NOS-DWR)

veral fault movement quadrilaterals established along this section of the ndreas fault in 1964. No evidence of ontal or vertical displacements indic- of fault movement has been detected y of these sites.

RSE-LEVELING: VICINITY OF CAJON PASS OS)

is traverse-leveling network extends ximately 10 km. through Cajon Canyon rosses the San Andreas fault at Lone Canyon. Observations for horizontal displacements in 1949 and 1963 and several relevelings since 1935 have revealed no evidence of fault movement.

FAULT MOVEMENT QUADRILATERAL: "DEVIL" SITE (NOS/DWR)

This small survey figure, located astride the San Andreas fault at Devil Canyon northwest of San Bernardino, was established in 1964. Annual reobservations prior to 1971 produced no evidence of lateral movement. The 1971 survey, however, indicated right-lateral displacement of approximately 1.5 cm between the 1970-71 surveys (Miller, 1972). This apparent change in movement behavior may be related to similar changes in trend noted on two nearby quadrilaterals located on the San Jacinto fault at Rialto and Colton. Both right-lateral movement of a few millimeters per year and differential subsidence across the fault had been recorded at both of these sites since 1964. Resurveys of these two sites, completed at the same time as the 1971 resurvey at the Devil site, indicated a reversal of the previously observed movements.

TRAVERSE-LEVELING: VICINITY OF WHITEWATER (NOS)

Repeat leveling at this site since 1935 has not revealed any vertical changes of significance. The original measurements for horizontal displacement were accomplished in 1950 and have not been repeated.

LASER STRAIN-METERS: PINYON FLAT (UCSD)

The University of California, San Diego, is operating three long-base (800 meter) laser strainmeters at Pinyon Flat between the San Andreas and San Jacinto faults (Berger and Wyatt, 1973). Observations were begun in 1971 on a north-south oriented instrument; an east-west arm was added in 1972, and the final northwest-southeast component was added in 1973. The dominant signal is an apparent annual strain cycle with an amplitude of approximately 1×10^{-6}. Several years of continued operation will be required to assess the secular strain rate.

TRIANGULATION: IMPERIAL VALLEY (NOS)

During the mid-1930's, NOS established a network of triangulation throughout the Imperial Valley as a part of the national geodetic control network (Miller and others, 1970). On May 19, 1940, the magnitude 6.7 El Centro earthquake produced right-lateral strike-slip displacement along the Imperial fault near the international boundary. As a consequence, the geodetic network was reobserved during 1941. Relative displacements across the Imperial fault reached a maximum of over 9 feet with the magnitude of displacement diminishing rapidly with distance from the fault. Right-lateral displacement of approximately 2.5 feet was indicated between stations on opposite sides of the Valley near the border, but there was no evidence of deformation in the net north of the Imperial fault. Reobservations in 1954, however, indicated right-lateral deformation primarily in the region north of the Imperial fault, suggesting northwestward strain migration after the 1940 earthquake. Reobservations in 1967 indicated little change from those of 1954, supporting the supposition that the displacements of the previous 13-year period (1941-54) were associated with the 1940 earthquake.

Considering the entire period covered by these surveys, 1934-67, there is (a) no clear indication of right-lateral strain accumulation in the northern part of the network, including that portion which crosses the San Andreas fault east of the Salton Sea, and (b) in the southern part of the network, the apparent lateral displacement across the 100-km wide valley is about 5 feet, or an average rate of about 4.5 cm/yr over the 33-year period. However, since a significant portion of this total displacement is probably attributable to the 1940 earthquake, a long-term rate of strain accumulation is not known.

GEODIMETER MEASUREMENTS (CDMG/USGS)

Parkfield-Maricopa

Several long (20-25 km) Geodimeter lines have been periodically remeasured between Parkfield and Maricopa since Greensfelder and Bennett (1973) and S and others (1973) have summarized the Geodimeter observations in this regio Since initial measurements in 1959, l in the Parkfield-Cholame region indic length changes of approximately 25-30 (1.0+ft.) consistent with right-later movement. These line length chang reflect a combination of right-latera creep, the offset accompanying the 19 earthquakes and, presumably, a compon of strain. However, the net change i length of lines further south through Carrizo Plains is much smaller than t north, and the changes on many of the in this region indicate significant e west extension during the period 1969 This is also true of lines throughout remainder of the locked segment of th Andreas fault southeast to San Bernar This time period coincides with a cha in measurement systems, however, and apparent displacements may be the res of a bias between the two systems. H ever, numerous measurements elsewhere the network do not indicate a consist bias nor is there a completely satisf tory explanation to account for one.

CDMG scheduled more frequent remea ments of selected lines across the Ca Plain during 1972-73. Length changes several centimeters were observed ove period of months on some but not all The apparent amplitude of these short period changes diminished to an insi cant level during 1974.

Maricopa-Cajon Pass

The most significant aspect of th Geodimeter data in this region i suggestion of a non-linear trend in of the line length changes. Greensf and Bennett (1973) have noted that m lines indicate shortening during the 1965-68 followed by an apparent leng during 1969-71. Again, this later p coincides with a change in measureme tems, so these length changes may no tectonic origin. Nevertheless, it c concluded that during the fifteen-ye period of measurement, 1959-74, the length change on lines associated wi

ndreas fault in this region does not
ct fault movement.

of Cajon Pass

ly a few Geodimeter lines were orig-
y established in the greater San
rdino-Redlands region when this
am was initiated in 1959. Several
ines were added along the San Jacinto
near Perris Reservoir in 1966 and
er south to Borrego Valley in 1970.
g 1973-74 the USGS incorporated many
ese lines into an expanded network
ing the San Andreas-San Jacinto-
ore fault systems.

odimeter measurements in this region
always been difficult because of
pheric conditions and the large
tion differences encountered on many
. Consequently, the pre-1969 measure-
, in particular, are not considered as
ble as measurements elsewhere in the
rk. From the limited data available,
n be concluded that the line length
es in this region have been nominal,
here are no changes clearly indica-
of either fault movement or strain
ulation.

RY

e various geodetic investigations
cted along the San Andreas fault in
ern California during the past 40
reveal no evidence of horizontal
slippage. More significantly, there
ttle evidence from these surveys to
st any appreciable lateral strain
ulation. The only evidence of strain
ulation occurs in the southern end of
mperial Valley with deformation dis-
ted across the entire 100 km width
e Valley.

ere is a corresponding absence of
rential vertical movement across the
ndreas fault during the past four
es. On a larger scale, however, the
ts of extensive repeat leveling dur-
he past decade indicate significant
t throughout the Transverse Ranges.

llectively, these data suggest that
is very little observable strain
accumulation taking place along the San Andreas fault. If the fault is locked to some considerable depth, strain accumulation at the surface would be so small that the available geodetic techniques are not able to resolve it. A dislocation model of the San Andreas fault with a locked zone at least 30 km deep predicts the geology and seismicity of the Transverse Ranges more accurately than a corresponding model assuming a shallower locked zone. The strain field calculated at the surface from the model has a maximum rate of change of less than 0.3 microstrain per year. Thus, in order to observe strain accumulation, geodetic techniques with a precision of at least 1×10^{-6} may be necessary with repeat observations spanning a period of 10 years or more. Since this precision has only recently been achieved, several years of continuing observations may be necessary before strain accumulation can be observed. In order to map the strain field and estimate the depth of the locked zone, geodimeter measurements should be extended 100 km on either side of the fault.

The uplift detected in the Transverse Ranges during the past decade suggests that leveling surveys and/or tiltmeter arrays may produce more immediately useful data than horizontal surveys. In 1968 several southern California counties, the City of Los Angeles, and the NOS established a cooperative leveling program, parts of which extend into the Transverse Ranges. Periodic releveling of this network with some extensions to improve coverage in the Transverse Ranges would provide an effective measure of long-term regional deformation, relative displacements at fault crossings, and a base for detection and surveillance of anomalous changes.

Finally, Geodimeter measurements, fault-movement quadrilateral reobservations, and leveling in the central Transverse Ranges suggest the existence of both horizontal and vertical deformation of a relatively localized and episodic nature. Whether these apparent anomalies are an expression of near surface stress changes or are due to some variation in basic tectonic forces is unknown.

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STRONG MOTION AND MICROACOUSTIC INSTRUMENTATION ALONG THE SAN ANDREAS FAULT

By William W. Wells and C. Forrest Bacon
California Division of Mines and Geology

1971, California Legislature enacted he Governor signed into law, Chapter Division 2 of the Public Resources (SB 1374), to establish and monitor tewide Strong-Motion Instrumentation am for recording earthquake motion in sentative geological environments and sentative structures throughout the .

e California Division of Mines and gy was directed to organize and or this program with the advice of visory Board appointed by the Geologist. The present Board of en members consists of engineers cientists with technical competence gineering seismology, as well as rep- tatives of local government, state ederal agencies, and private organi- ns.

strong-motion seismograph (also d accelerograph) is an instrument ned to record the stronger vibrations d by earthquakes. It does not record r vibrations, but produces records when an earthquake producing an eration greater than 0.1g takes place y and triggers the instrument. The of seismograph used for recording earthquakes is too sensitive for this nd is usually driven "off-scale" be- the strong-motion instrument records.

is vitally important that strong- n instruments be located on soil and formations and along faults wherever ruction is planned so that the ground n recorded may be studied and consid- in construction design. It is also sary to have strong-motion instruments rious types of structures to evaluate ehavior of different structure designs g an earthquake.

Because soil and rock types vary greatly across the state, sites are chosen that reflect the variety of California's geology. It is necessary that there be a statewide program to assure that there will be a coordination of effort and a scientifically sound distribution of instruments.

At this time, the Division of Mines and Geology is installing strong-motion instruments as follows:

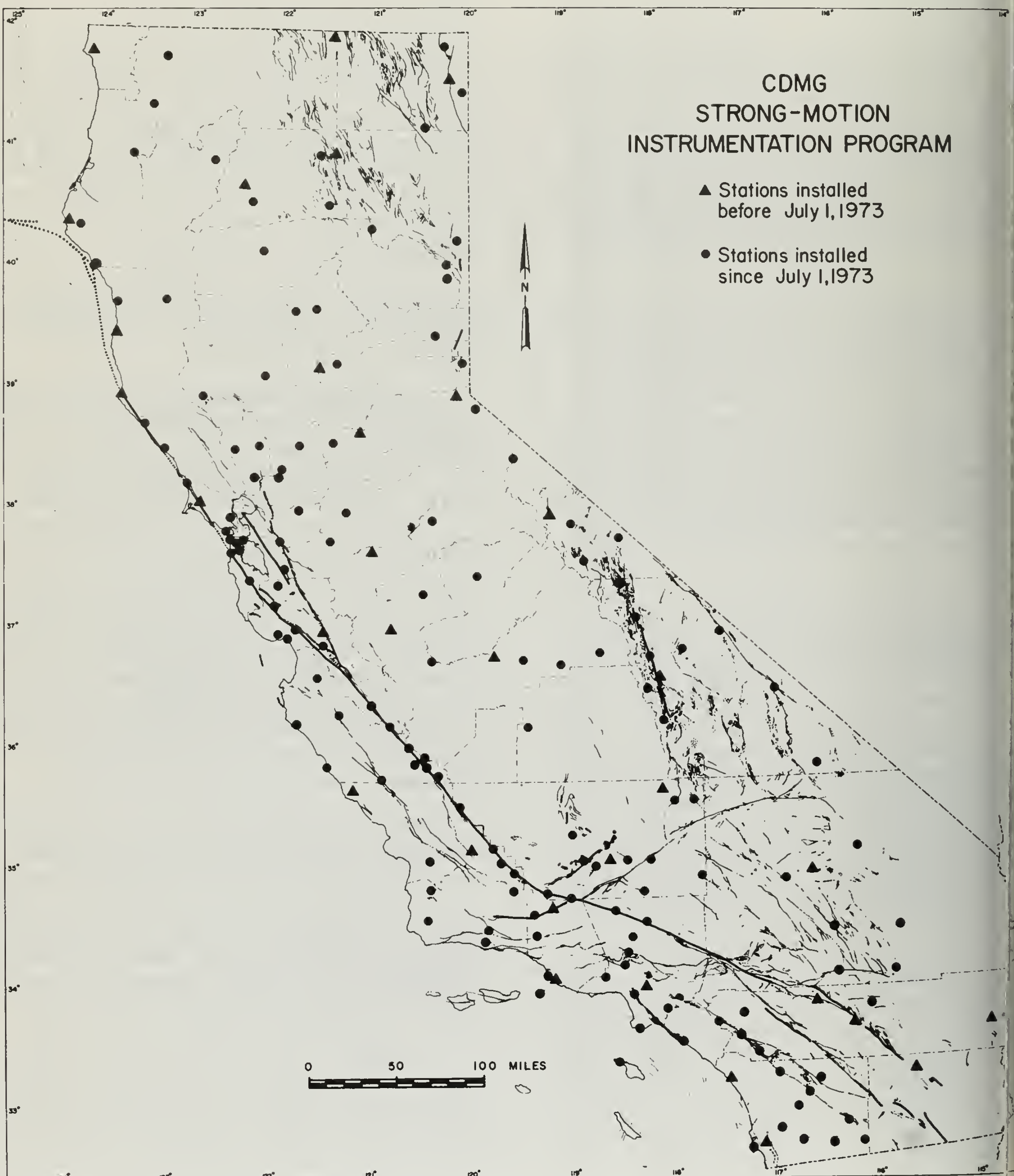
1. In geographic areas not yet covered by instrument installation by other organizations,
2. On representative soil, rock and fault sites throughout the state, and
3. In a broad group of representative buildings and structures.

The State Strong-Motion Instrumentation Program is carried out in cooperation with other agencies; mainly with the Seismic Engineering Branch of the U.S. Geological Survey, California Institute of Technology, Department of Water Resources Dam Safety Division, and the Structural Engineers Association of California.

All state instruments are integrated into the strong-motion network of the U.S. Geological Survey. The U.S. Geological Survey collects and processes strong motion instrument records from any earthquake in California and makes the data available upon request to scientific and engineering organizations.

From the Salton Sea to north of Parkfield, the Division of Mines and Geology has installed 19 instruments along the San Andreas fault. California Institute of Technology has 22 proposed instrument sites along the San Andreas fault covering the same area. Most of these instruments have been installed or will be installed in the near future. (See map.)

In addition to the above, the U.S. Geological Survey and the Department of Water Resources has approximately 12 to 14 instruments either on or close to the San Andreas fault.



STIC EMISSION ALONG THE SAN ANDREAS FAULT

s part of an experimental instrumen-
on program, the California Division of
s and Geology has completed the first
e of a pilot study to monitor audio
uency microseismic activity along a
r fault zone. Preliminary results in-
te that this method may prove to be a
ul tool for predicting earthquake
vity. The idea that audible noise or
subaudible "sounds" may precede major
hquakes is not new. The literature
ribes numerous instances of the ex-
e agitation of animals over periods of
hours before actual major earthquake
ts. To test the credibility of these
ies, and others involving premonitory
riences of humans, Armstrong (1969)
ared the auditory response of man and
als, and discussed, in mathematical
s, their possible capabilities to de-
acoustic emission of the level that
ars prior to rockbursts and perhaps
re earthquakes. He concluded that
ss buildup may improve the acoustic
smission characteristics of the rock
even form "sound channels" so that
o frequency precursors may be heard or
cted at the surface. He suggested
sound with frequencies up to a few
hertz may travel far enough to be de-
ed and to give useful warnings of
low focus earthquakes for highly
mic populated areas.

icroseismic-acoustic methods have been
in mining and slope failure studies
e the development in 1939, of equip-
for the detection of popping and
king of rock which occurs just prior
tunnel wall failure or rockburst.

lthough some recent workers have lis-
d along faults for possible changes in
l of acoustic emission as indicators
mpending fault movement, results were
ppointing. Possible reasons for the
nclusive results obtained in these
riments include poor acoustic trans-
ion characteristics of the rock or
materials beneath the site chosen
the experiment; lack of acoustic emis-
due to insufficient stress buildup at the time of testing; or presence of creep zones which relieve stress continuously and prevent its building up to levels associated with acoustic emission. Extraneous noise such as that caused by car doors, aircraft, wind, blasting, internal combustion engines, construction activity, thermal expansion and contraction of rock, and insects and animals can also mask acoustic frequency microseismic activity. Probably the greatest single reason for inconclusive results has been that insufficient time and effort were spent in monitoring in the right location.

The present pilot study was designed not with the idea of spending long periods monitoring particular stations, but to determine the factors that constitute a good acoustic listening station. Where should the station be located? What should be its physical relationships to the fault being monitored? What kind of geologic materials should be present at and near the site? What kinds of fault activity are most likely to create detectable acoustic emission? What kinds of equipment should be used and in what configuration? What operational problems can be expected and how can they be minimized? The discussion which follows will attempt to bring out the answers obtained so far and to indicate which questions need further consideration.

SELECTION OF STATIONS

Brune and Allen (1967) observed that micro-earthquake activity is least along the southern central section of the San Andreas fault, between Cholame and Valyermo, but increases notably along the fault trace both to the south and to the north of this section. The level of micro-earthquake activity ranges from virtually nil in the segment between Cholame and Valyermo to more than 75 shocks daily in the Imperial Valley section.

It should be emphasized that Brune and Allen were dealing with true micro-earthquakes at frequencies of 20 hertz and below. On the other hand, the present study emphasizes those frequencies well up in the audible spectrum in the range of 150 hertz to several thousand hertz, and is concerned with the detection of micro or small scale fracturing sound, which according to Scholz (1968a), begins at about half the fracture stress, in rock, and accelerates to a final burst of activity just before failure.

The segment of the San Andreas fault between Parkfield and the Carrizo Plains was selected for part of this study for two reasons: first, the work could be coordinated with other projects of the Division of Mines and Geology in that area and second, by selecting an array of stations that extends in both directions from the northern boundary of the "locked" or quiet segment of the fault, we sought to test whether stress is indeed building up around this critical zone. For these reasons, six stations were established along a 160-mile stretch of the fault (Figure 1): 1. at Gold Hill, just south of Parkfield, in an area of increased earthquake activity; 2. at the southern end of Cholame Valley very close to the northern end of the "locked" zone; 3. at the northwesterly bend in the fault near Mt. Abel; and 4, 5, and 6 located to test for stress buildup within the southeastern part of the "locked" zone between Frazier Park and Palmdale.

We tried to locate the stations immediately adjacent to the fault on large bodies of hard rock with above average acoustic transmission characteristics. This was considered necessary because as Armstrong (1969) has pointed out, transmission ranges for high frequency sound, in rocks under normal pressure, are very short, and this indicates that there would be only a marginal possibility of detecting usable acoustic emission sounds--and then only under very favorable circumstances.

Armstrong (1969) also points out that rock Q (specific attenuation factor) values are known to increase with pressure, thus improving acoustic transmission characteristics, and this may substantially increase the ranges of local transmiss[ion] in regions of high stress. This effe[ct] could significantly improve the observ[a]bility of preliminary acoustic emissi[on], particularly for shallow-focus earthq[uakes] with strain fields that extend to the surface. Armstrong estimates, that f[or] rocks with normal Q values of about 1[00], the maximum range of transmission for sounds of 1000 hertz frequency would [be] 3000 to 4000 meters. If the rock bec[omes] stressed, which might raise the Q val[ue to] 1000, the maximum sound transmission [range] may be increased to as much as 30,000 [to] 40,000 meters.

For regions under normal stress co[nd]itions, it can be seen from the forego[in]g that if the origin point for acoustic emission lies as far below the surfac[e] as say, 1500 meters, the transducer m[us]t be located as near the fault as possi[bl]e and in rock with the best possible ac[ous]tic transmission characteristics. Su[ch] rock is difficult to find adjacent to [t]he San Andreas fault in the area of this study. Hard rock, where it is presen[t], commonly is much fractured or is deep[ly] altered or both. As can be seen from [t]he foundation materials list in Table 1, [a] compromise in rock hardness was somet[imes] necessary in order to site a station [at a] critical location.

EQUIPMENT

The equipment used in the pilot st[ud]y includes units on hand and units whic[h] could be borrowed. The microseismic [or] acoustic detection devices consist of t[wo] Seismitron units, manufactured for us[e in] mines and tunnels. The Seismitron am[pli]fies sound up to 2.5 million times a[nd] can detect movement that is smaller [th]an the diameter of a hydrogen atom - (4.16×10^{-8} cm). In use, the instru[ment] probe is placed in the end of a six-[foot] drill hole and the mouth of the hole [is] filled with packing to minimize extr[aneous] sounds (Figure 2). The operator lis[tens] to the amplified sounds using earpho[nes] and may, at the same time, record th[e] signals on magnetic tape, an oscillo[graph] or a chart recorder.

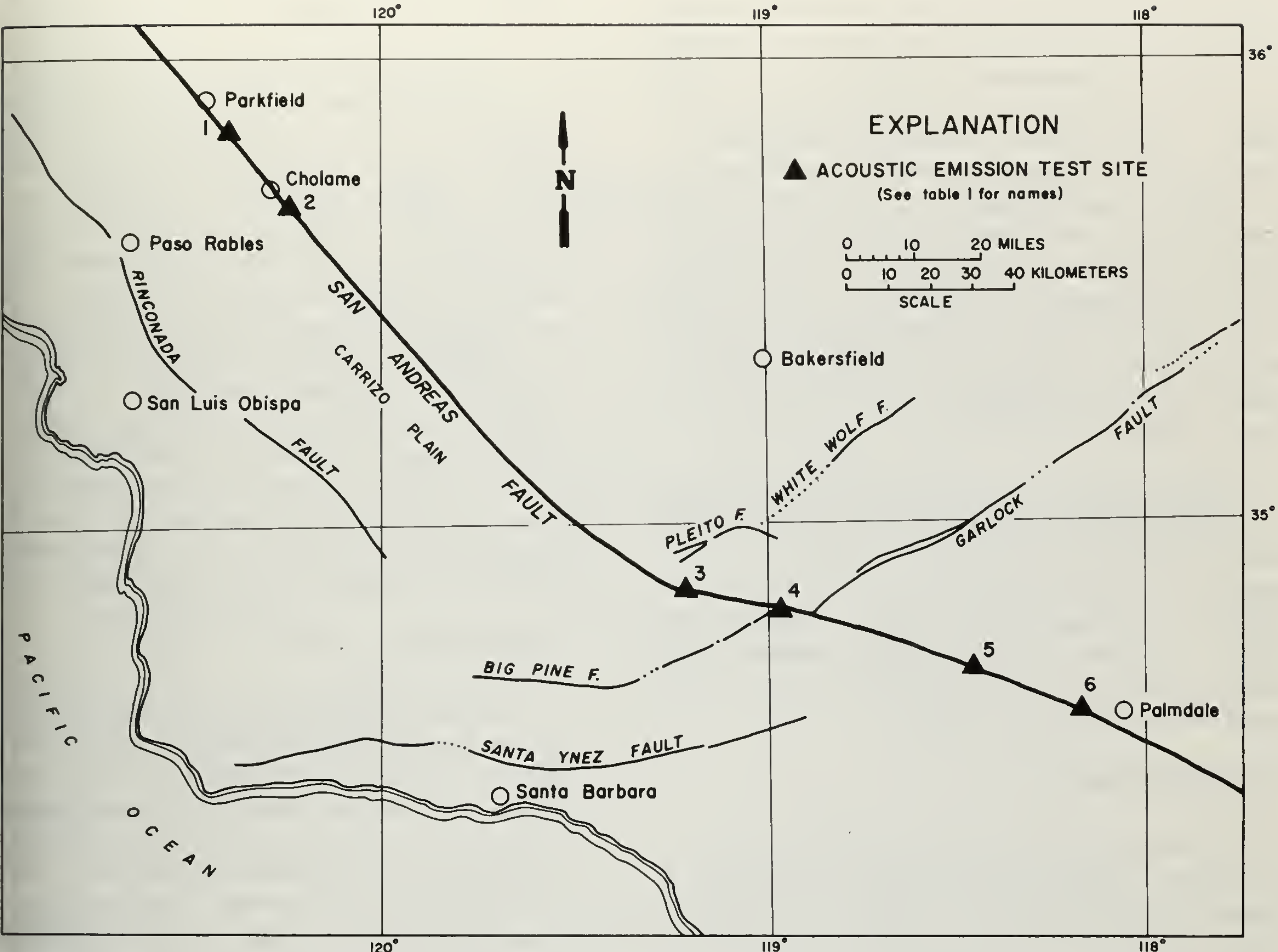


Figure 1. Index map showing the locations of the microacoustic test stations.

Station	Foundation Material	Highest Count Per 15 Min.	Lowest Count Per Hour	Average Count Per Hour
;old Hill	Limestone & Gabbro	7	0	2
;holame	Greenstone Wedge & Shale	1	0	3
;aballo	Cemented Breccia	11	1	12.2
'razier	Quartz Monzonite	3	0	3.2
.eona	Sandstone	1	0	0.6
'elona	Schist	4	0	2.6

TABLE 1

Acoustic Emission Event Count Analysis

The operator must eliminate unwanted or extraneous sounds which may very closely resemble true acoustic emission. Sources of such extraneous sounds are, for example, the crushing of a sand grain as the probe settles, heat related expansion or contraction, or movement of sand grains or pebbles down slope. To overcome this problem, two instruments are used simultaneously in holes located 25 feet apart. The instruments are connected and balanced to provide binaural or "stereo" recording and listening. Any signal which does not occur on both channels is discarded as local, unwanted noise.

Signals are recorded on magnetic tape at a speed of 1-7/8 inches per second for later playback and analysis in the laboratory. Detailed, time-regulated notes are taken during each recording and these, together with digital counter information, can be used to identify any signal received on either channel.

LABORATORY ANALYSIS

Equipment used in the laboratory analysis of the taped records includes a frequency-calibrated triggered oscilloscope, high and low cut filters, a 4-speed tape recorder, a chart recorder, and appropriate bridge rectifiers, matching networks, and filters. The chart recorder is used to make a permanent record for comparison of amplitudes and overall activity in any given time period. Tapes are played back with audible sound and with a portion of the signal fed to the frequency-calibrated oscilloscope. Each acoustic emission event waveform is photographed and analyzed for overall frequency content, arrival times, and particular frequency bands using high and low cut filters. Analysis of signals for frequency content is a time-consuming but worthwhile part of this program, and will continue for a period before all the results are complete. Armstrong (1969) has discussed in some detail the problems involved with the use of various frequencies. In addition, a small computer program is being developed which will consider amplitude spectra, cross correlation between channels, anisotropy and P-wave travel time and also provide a crude location technique.

At the beginning of this project, it was assumed that the minimum time period needed to obtain representative observations at each station should be similar to those used for underground work, or about 15 minutes. However, wide variations in average count per unit time were found in tests made over periods of one to two hours and even wider variations were noted in short period tests made on different days. It became apparent that the minimum recording period should be at least one hour and that periods of two or more hours would prove useful, particularly when the tests are separated by a period of a week or longer. Table 1 lists some average and specific counts for the various stations.

FUTURE WORK

Probably the greatest single problem experienced in the tests is the identification and elimination of extraneous noise. Wind can be particularly troublesome because it sometimes blows hard enough and continuously enough to mask all but the strongest acoustic emission events. However, the noise that is most difficult to distinguish from true microseismic events is that produced by expansion and contraction of rocks due to heat changes. Despite the use of dual probes and other precautionary measures, a sizeable percentage of the events recorded during this study are probably from this source. It is possible that, because of rock type and exposure, this phenomenon may account for a major part of the anomalously large number of events recorded at Caballo station. The best and most obvious method of improving the signal-to-noise ratio is to place the transducers in deep drill holes. In addition to deep drill holes, more than two probes will be used in the next series of tests, to provide an accurate means of locating emission points in three dimensions in the earth. Also, for the next series of tests, each site will have an equipment vault so that time-switched or signal-triggered time-delayed recording can be made from a continuous loop recording while equipment is left unattended.

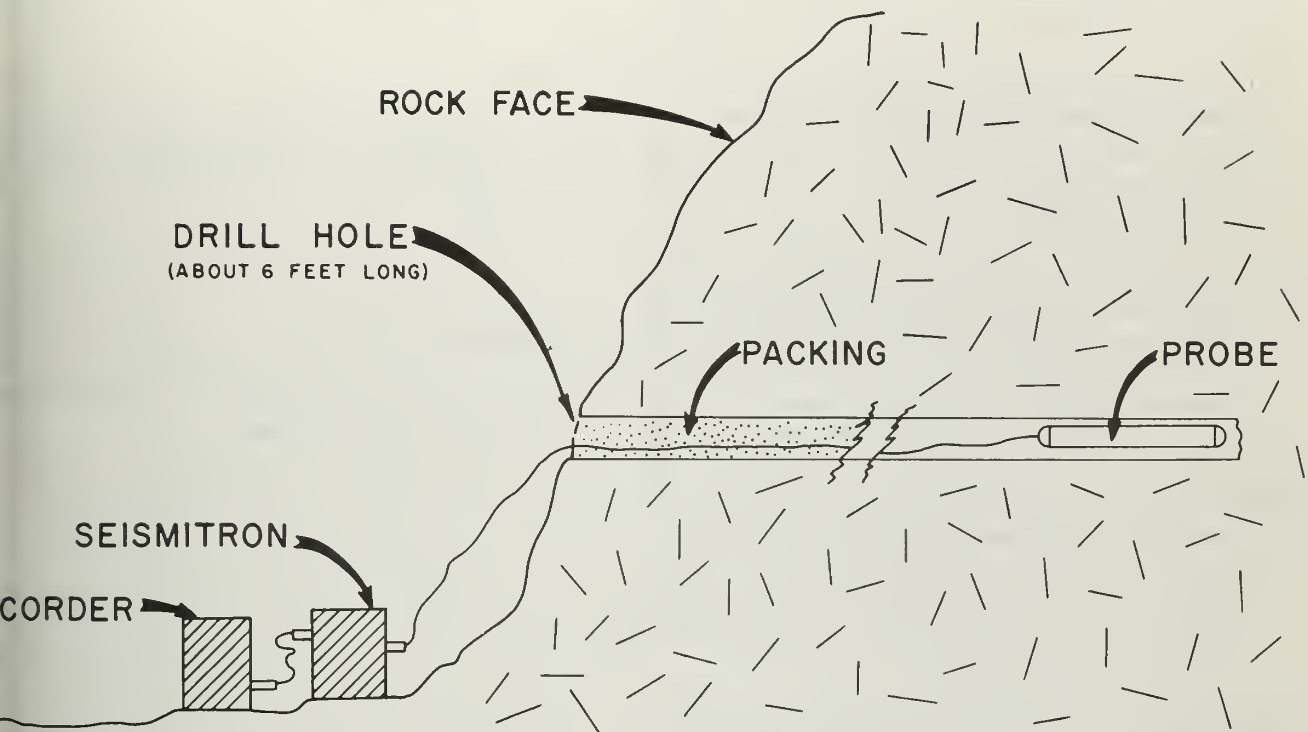


Figure 2. Typical installation of microacoustic detection equipment used for this pilot study.

periods of several hours or several

USIONS

is pilot study determined the feasi-
y of monitoring acoustic phenomena
ossible applications in the predic-
of earthquakes along the San Andreas
. Field measurements to date were
ntended to monitor earthquake precur-
as such. The project successfully
mined: 1) that audio frequency micro-
ic activity can be detected; 2) what
 of areas would make the best sites
urther study; and 3) what types of
umentation and techniques would be
successful for this purpose.

boratory analysis of the pilot project
is still continuing, but results to
indicate that the method may hold promise in the field of earthquake prediction. Acoustic emissions were definitely detected in small but varying amounts at several of the stations, although the type and level of that activity can vary widely from one measurement interval to the next.

The greatest problem encountered, the identification and elimination of similar sounding noise from thermal expansion and contraction of rock will be minimized in the next phase of operation through use of deeper drill holes and multiple instrumentation.

The critical question, whether detectable variation in the level and type of acoustic microseismic emissions actually occur just prior to earthquake-causing movements along a given fault, remains to be answered. The technique, instruments and theory are available, but their success in predicting damaging earthquakes can be proven only by experience with real earthquake events.

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ACKNOWLEDGEMENTS

Reviewed by Donald A. Rodgers and Tousson R. Toppozada.

EARLY AND MIDDLE EOCENE SHORELINE OFFSET BY THE SAN ANDREAS FAULT, SOUTHERN CALIFORNIA

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nlo Park, California 94025

ACT

leogene strata crop out extensively e Transverse Ranges. The lithofacies aunal assemblages of lower Paleogene a indicate widespread open-ocean tions with a shoaling towards the and northeast. The shoreline for deposits is inferred to have been of the San Andreas fault zone in the nt Mojave Desert region.

early Eocene time a Borderland ography had developed west of the San as fault and was well developed in the e Eocene. The marine environment ed northwestward against the then ent San Rafael High that was bounded e east by a northwest oriented marine ment. The east margin of this embay- shoaled against granitic terrane in ine Mountain-Piru Creek area. The extension of this shoreline is now ted nearly east-west and trends toward an Gabriel fault zone.

e only Paleogene strata known to crop ast of the San Andreas fault zone are e sediments of the Maniobra Valley, east of the north end of the Salton These rocks unconformably abut the granitic terrane by depositional .

is inferred that Eocene strata of the Mountain-Piru Creek area and the bra Valley have been separated 220 to m (260 km is best fit) by right-slip ing on the late Tertiary San Andreas .

DUCTION

leocene sedimentary rocks of the verse Range suggest that open-ocean tions existed east of the present of the San Andreas fault (Reed and ster, 1936; Sage, 1973). Physiographic opment of a borderland by early Eocene time created more restricted seas that shoaled principally west of the San Andreas fault zone.

Assuming no late Tertiary crustal rotation, it appears that by the middle Eocene an east-west oriented marine basin had developed in the Transverse Range area. The northeastern shoreline of this basin was located along the southwestern limit of the Pine Mountain-Piru Creek area (Fig. 1). This shoreline trends towards the San Gabriel fault, but the only Eocene rocks to the east of this fault are now located in the Maniobra Valley east of the San Andreas fault zone (Fig. 1). This report briefly describes the middle Eocene lithologies (concentrating on the conglomeratic facies) from these two areas.

Pine Mountain-Piru Creek area, Paleogene lithology

Thick, often impenetrable, brush cover prevents extensive lateral observations of the Eocene section of this area. Measured sections, however, from the Mutau Flat, lower Piru Creek and Canton Canyon (Fig. 1), where access is relatively easy and exposures are good, permit the geology to be reconstructed in three dimensions.

Mutau Flat. A large scale geologic map of Mutau Flat and vicinity has recently been compiled by Givens (1974) from the unpublished theses of Schlee (1952), Kiessling (1958) and Jestes (1963). The middle and upper Eocene strata in this area have a combined maximum thickness of about 4,700 m. These rocks are probable equivalents of the Juncal and Matilija Formations of the Santa Ynez Mountains (Givens, 1974). The Eocene basement contact is faulted in most exposures, although locally basal beds lie with depositional unconformity upon the plutonic basement.

The lower 3,000 m of section is principally mudstone and conglomerate, in which individual beds vary considerably in thickness. The mudstone thickens abruptly toward the south-southwest, away from the

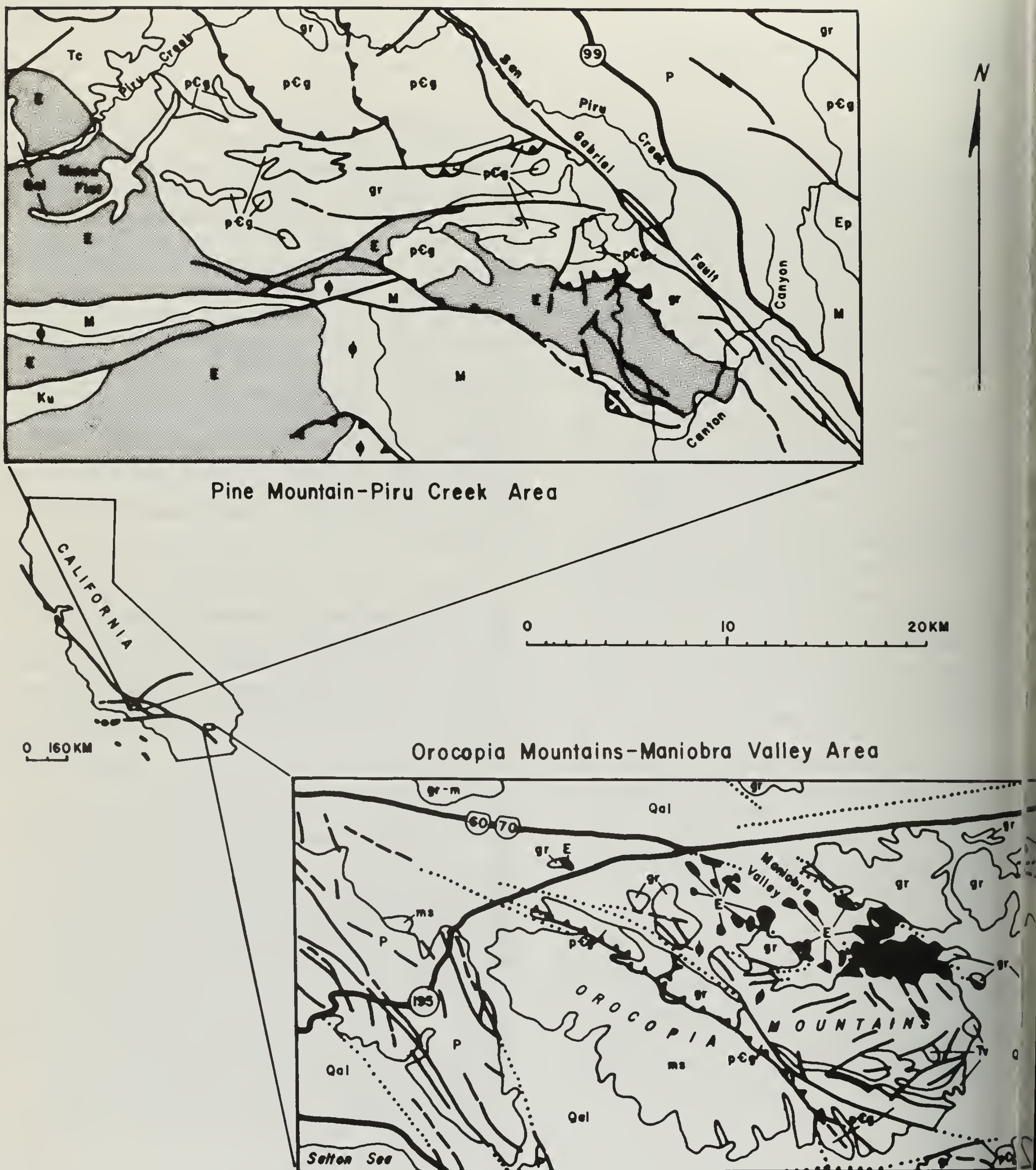


Figure 1. Distribution of Eocene strata in the Pine Mountain-Piru Creek area and the Orocopia Mountains-Maniobra Valley area.

e basement contact, whereas the
omerate thins in this direction and
ately wedge out within several kilo-
s of the basal contact.

nglomerate exposed in a fresh roadcut
e northeast end of Mutau Flat contains
rounded pebbles and cobbles admixed
large angular granitic blocks up to
n size. The composition of the
es and cobbles is: granite and
diorite 30-40 percent, gneiss 10-15
nt, quartzite 10-15 percent, gray,
, and red volcanic material 20-35
nt, and sandstone 5-15 percent.
eling and clast imbrications suggest
the material was deposited by currents
ng toward the south and southwest.

Piru Creek. For the lower Piru Creek
ost detailed large-scale geologic maps
npublished theses of Kriz (1947),
erd (1960) and Jestes (1963). The
contact mapped in the Mutau Flat area
en basement and Paleogene strata can
aced eastward to the lower Piru Creek
1), where the granitic basement rocks
hrust over a conglomerate. The
gene sedimentary sequence is as much
500 m thick and is unconformably
ain by the Sespe Formation. Similar
e Mutau Flat area, the sequence is
ipally conglomerate, shale, and
tone, although sandstone of late
e age is an important component in the
part.

lower Piru Creek the sequence is
om to top); 1,000 m of conglomerate,
m of shale and siltstone, 650 m of
omerate, 1,500 m of shale and silt-
and 1,000 m of medium bedded,
nlike sandstone. Except for a few
es of foraminifers of possible
cene age from the lower conglomerate
, 1947), fossils diagnostic of age
not been reported from the lower two
omerate and lower shale and siltstone
; consequently, the age of the lower
of the sequence is uncertain. Middle
e foraminiferal assemblages have been
cted from the upper shale and silt-
unit (Howell, 1974).

In composition conglomerate clasts are 25-50 percent granite and granodiorite (one variety having 2-3 cm long pink potassium-feldspar phenocrysts), 10-20 percent gneiss, 0-10 percent quartzite, and 40-60 percent gray, green, red, and purple volcanic material. A few clasts are as large as 3 m; however, the predominant size range is from 1 cm to 1.5 m, and the mean size is 8 cm. Although the largest clasts are granitic and gneissic, there is a significant number of "Poway"-like red volcanic clasts in the 4-25 cm size range.

The granitic and gneissic clasts are megascopically similar to basement rock cropping out north of the Paleogene exposures. Numerous sedimentary structures, including clast imbrications, rip-ups, cross-beds, and channels, consistently indicate a north to south flow direction.

Canton Canyon. Detailed maps of the Canton Canyon are 4 km east of lower Piru Creek, are contained in the unpublished theses of Shepherd (1960) and Kriz (1947) and an unpublished map by J. C. Crowell (personal commun., 1974).

The Paleogene sediments, which are almost entirely fine grained, are in fault contact with the granitic basement terrane along the east extension of the boundary fault described above in the Mutau Flat and lower Piru Creek areas. The basal rocks in Canton Canyon are lenticular beds of conglomerate and sandstone, from which middle Eocene megafossils have been collected (Shepherd, 1960). The bulk of the section is 3,300 m of shale and siltstone (Shepherd, 1960). Overlying this is 400 m of massive sandstone overlain by a non-marine fluvial sequence of siltstone, sandstone, and conglomerate. This latter unit unconformably underlies the nonmarine Sespe Formation.

Pine Mountain-Piru Creek area, Paleogene paleogeography

The absense of good faunal control for precise biostratigraphic correlation and the rapid lithofacies changes along strike limit any attempt to reconstruct ancient paleogeographies for all the different stages of the Paleogene. It does appear, however, that for much of the Eocene a shoreline was located in the Mutau Flats area and extended eastward (Fig. 2). The evidence for this includes: (1) the middle Eocene buttress unconformity in the Mutau Flat area, (2) large angular blocks of local basement in the conglomerates of Mutau Flat and lower Piru Creek, (3) the rapid wedge out of conglomerate in the Mutau Flat area towards the west and south, (4) the north to south flow directions inferred for the Paleogene strata of Mutau Flat and lower Piru Creek and (5) the presence of a nonmarine middle or upper Eocene facies in the Canton Canyon area.

Maniobra Valley, Paleogene lithology

The Eocene rocks (Maniobra Formation of Crowell and Suski, 1959) in the Orocopia Mountains are the only rocks of this age east of the San Andreas fault in southern California. Detailed maps of this area are included in the unpublished theses of Williams (1956) and Gillies (1958) and in the published report of Crowell and Susuki (1959). Foraminifers reported by Johnston (1961) indicate that the stratigraphically lowest beds are probably early Eocene and remainder of the formation is middle Eocene.

The basal conglomerate, breccia, and sandstone beds are in depositional contact (buttress unconformity) upon granite. These coarse-grained facies grade to the southwest and west into finer grained rocks. Boulders as large as 9 m inferred to have been derived from the underlying and adjacent granite are incorporated in the basal conglomerate. Most of these large clasts are subrounded to angular. In composition the pebbles and cobbles of the conglomerate are quartzite, granite, quartz monzonite, granodiorite, gneiss, and slightly metamorphosed siltstone (Kirkpatrick, 1958). Unlike the middle Eocene conglomerates elsewhere in southern California no metavolcanic clasts occur here (Howell, 1974). The aggregate thickness of the conglomerate and inter-bedded sandstone is approximately 600

Overlying the coarse clastic facie approximately 900 m of interbedded sandstone and siltstone. These rocks principally exposed in the western pa the outcrop, where the underlying con erate and breccia have wedged out.

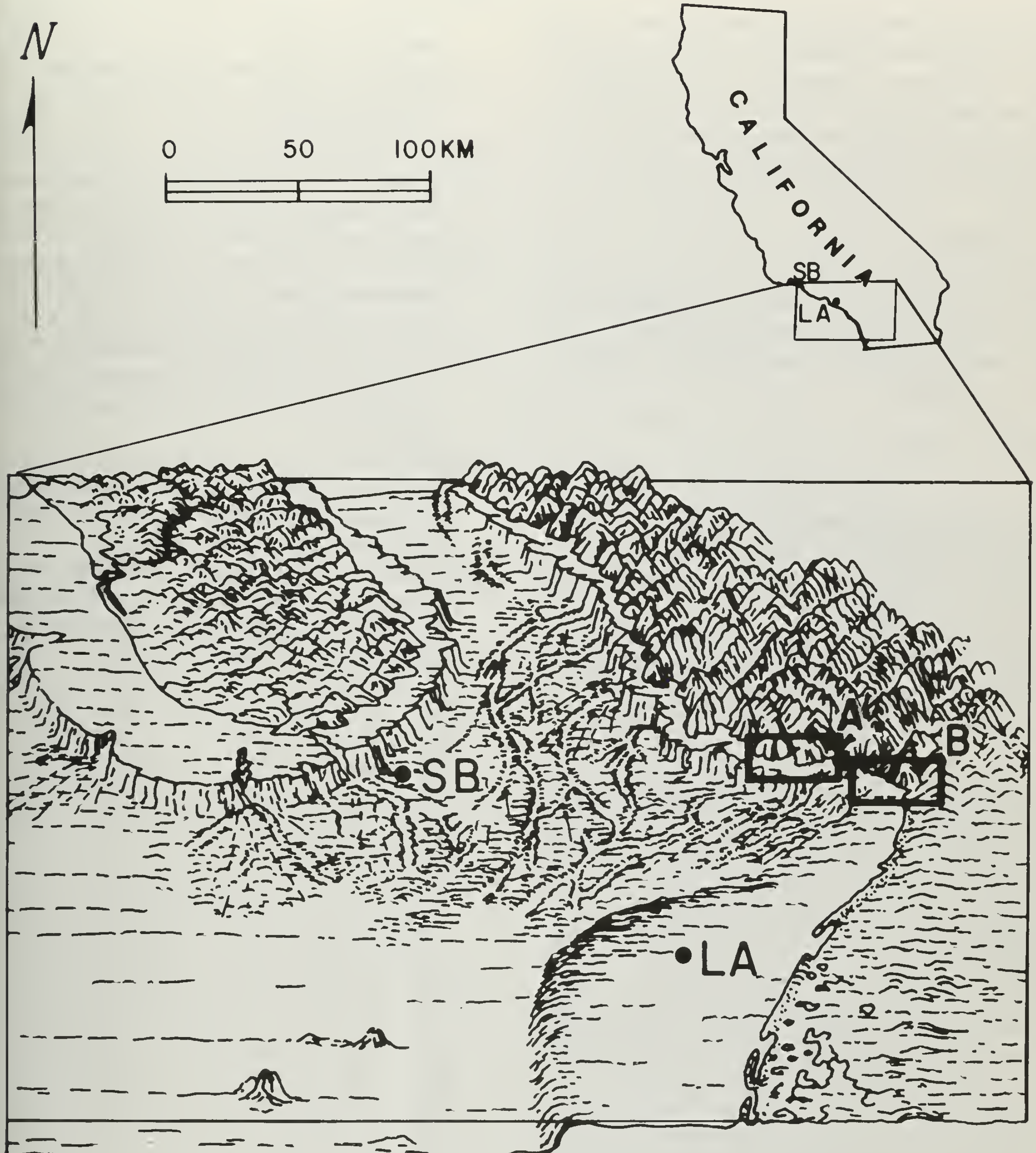
Maniobra Valley, Paleogene Paleogeogr

The conglomerates and breccia beds probably represent an environment of deposition on or near a marine shorel inferred from the following observati (1) the conglomerate abuts the granit basement with angular unconformity, (2) clasts within the conglomerate ar large as 9 m, (3) the composition of large clasts is the same as that of t local basement, (4) although most of clasts are rounded, some are angular "joint blocks", (5) the conglomerate appears to pinch out to the west and west where shelf faunules have been reported, (6) the fauna from mudstone associated with the conglomerate sugg inner neritic environments of deposit (Crowell and Susuki, 1959; Johnston,

CONCLUSION

Working from a suggestion from J. Crowell, Kirkpatrick (1958) correlate Maniobra Formation with similar-appea Eocene rocks northwest of the interse of the Big Pine and San Andreas fault He concluded that it was possible tha 310 km of post Eocene right-slip on t San Andreas fault had separated these areas.

It appears, however, that there ar nearshore early and middle Eocene lit facies in the southwest and south par the Piru Creek area that offer a more compelling match. Middle Eocene pale geographic studies for the Topatopa a Santa Ana Mountains and Simi Hills su an inferred middle Eocene east-west m embayment, the northeast limit of whi would have been in the Piru Creek are (Howell, 1974). The Maniobra Formati seem to represent the east limit of t



e 2. Middle Eocene paleographic reconstruction of southern California after a spastic adjustment for 260 km of right-slip on the San Andreas fault. Block A = Mountain-Piru Creek area; Block B = Orocopia Mountains-Maniobra Valley area; Santa Barbara; LA = Los Angeles.

embayment.

Because the exact position of the middle Eocene shorelines cannot be located, an accurate value of slip on the San Andreas cannot be determined. Slip of 220-280 km is compatible with the data, and 260 km establishes the reconstruction shown in figure 2.

ACKNOWLEDGMENTS

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MID-TERTIARY CONGLOMERATES AND THEIR BEARING ON TRANSVERSE RANGE TECTONICS, SOUTHERN CALIFORNIA

By Robert G. Bohannon, U.S. Geological Survey, Denver, Colo. 80225

RACT

oarse redbeds characterize mid-Tertiary inental sedimentary rocks in southern fornia. They include the Simmler, e, Plush Ranch, and Vasquez Formations, the formation of Diligencia, which are ably in part contemporaneous. These s contain locally derived conglomerates accumulated in several fault-bounded ns. These east-west trending basins associated uplift areas apparently sed the present trace of the San eas and San Gabriel faults and were offset by them.

DUCTION

id-Tertiary continental rocks in the sverse Ranges are characterized by se redbeds, which mark an interruption he extensive marine deposition that ailed in much of southern California ng the Tertiary Period. This phase of onics and sedimentation occurred about same time as, or just prior to, the in-ion of Tertiary volcanism in southern fornia and triple junction migration g the coast (Atwater, 1970), and just r to the inferred initiation of strike- faulting on the San Andreas system.
n order to understand the tectonic ework and sedimentologic history of ns in existence at that time, the ler, Sespe, Plush Ranch, and Vasquez ations, and the formation of Diligencia studied in 10 localities (fig. 1). ial attention was given the conglom- e facies and their clast types, prov- ce, and paleocurrent features. Con- erate analysis helped document basin ory and development; using this infor- on, individual basins were compared tigraphically and chronologically.

RELATIONS

ge control comes from fauna in under- g and overlying strata and from po- ium-argon age determinations taken on lt flows in three of the areas. The ral age relations of the mid-Tertiary rocks studied are shown in figure 2. Basalt dated in the Plush Ranch Formation yields ages of 17.4±3.7 and 19.6±1.1 m.y. (million years), in the Vasquez Formation 23.9±0.8 and 24.9±2.1 m.y., and in the formation of Diligencia 22.4±2.9 m.y. (Crowell, 1973). Although the dated rocks are not precisely the same age, the sedimentary sections containing these dated rocks possibly overlap in age and appear to be part of a unique tectonic and sedimentary phase which may have developed in different places through time.

BASIN DESCRIPTIONS

Simmler Formation

The Simmler Formation in the La Panza Range (fig. 1, no. 1) consists of coarse conglomerate and minor arkose. Angular clasts of arkose and rounded clasts of medium-grained biotite quartz monzonite, granodiorite and devitrified porphyritic felsites are the predominant clasts. Pebble imbrication suggests transport from southwest to northeast.

A thick section of Simmler occurs immediately northeast of the Nacimiento (Rinconada) fault; however, none occurs on its southwest side. This distribution and the paleocurrent indicators suggest that the Simmler Formation was derived off an active scarp at or near the Nacimiento fault (Vedder and Brown, 1968); however, clasts in the Simmler indicate a conglomeratic provenance. According to T. W. Dibblee (personal commun., 1974), nearby rocks across the fault are nearly all sandstone and shale, not conglomerate. This problem could be alleviated by assuming that conglomerate once existed in the proposed source but was now eroded, or that strike slip occurred on the Nacimiento fault during or after deposition of the Simmler Formation.

In the northern Cuyama badlands (fig. 1, no. 3), coarse conglomerate of the Simmler Formation contains clasts of medium-grained muscovite-biotite quartz monzonite, banded muscovite-biotite gneiss, rare aegerine-hornblende-

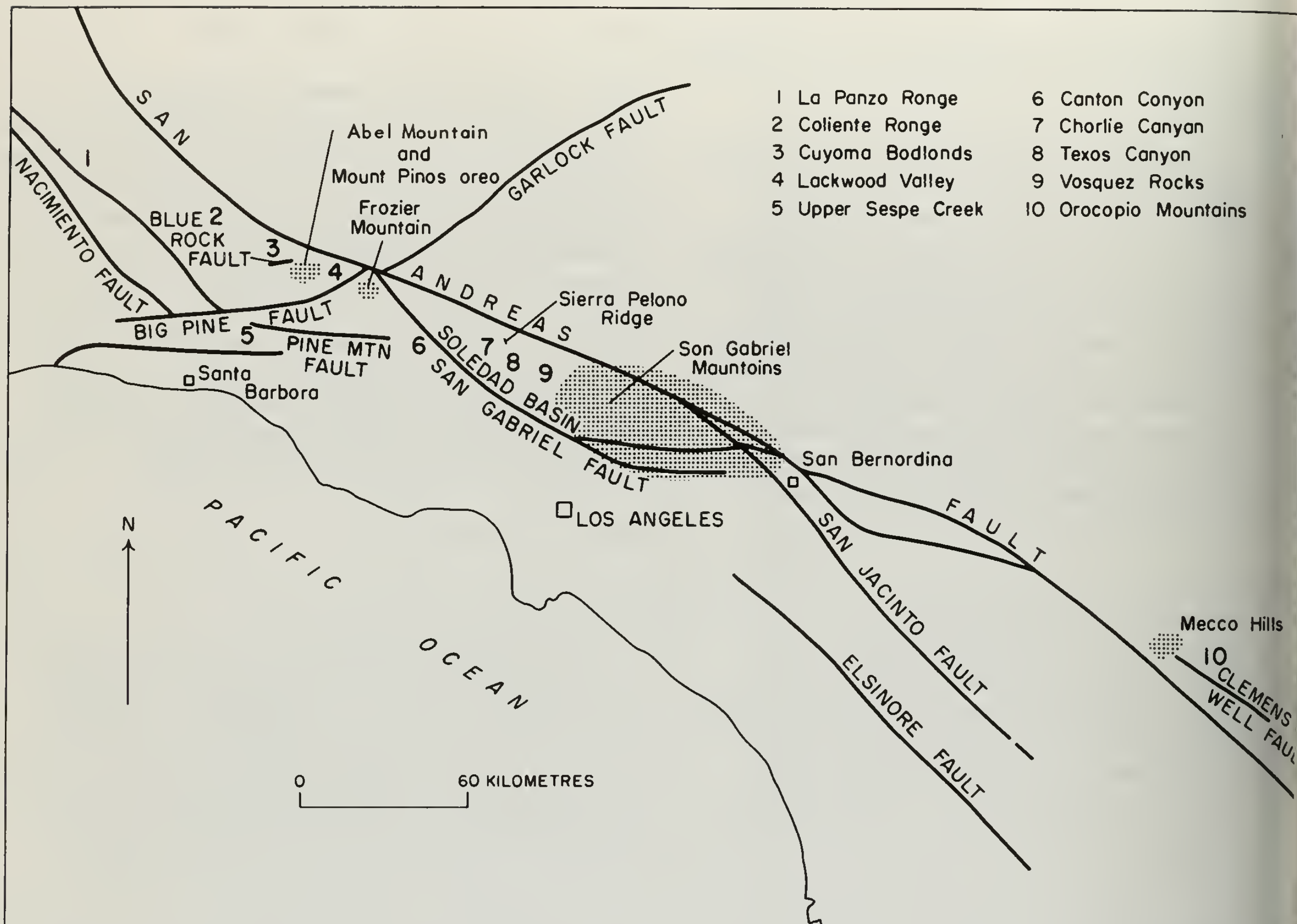


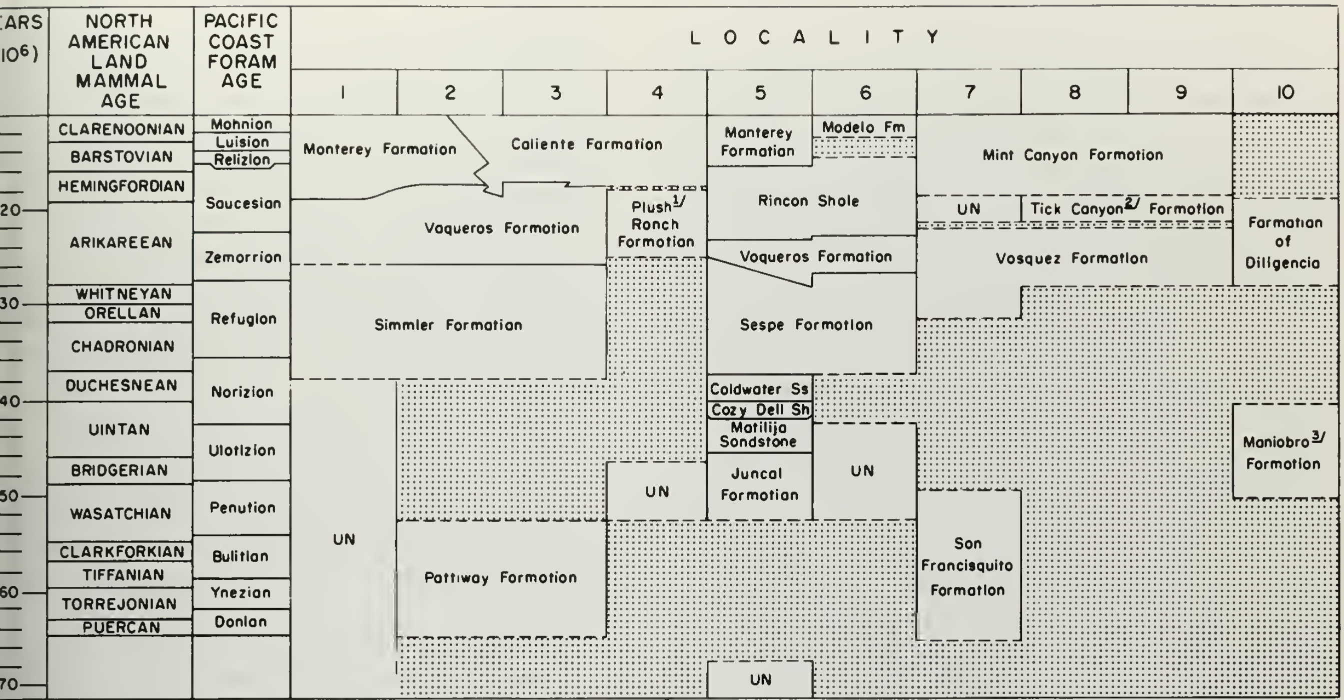
Figure 1.--Index map showing the location of the 10 study areas in southern California.

muscovite granite and, at a few localities, dacite, oxyhornblende welded tuff, and flow-banded rhyolite. Most of the section has paleocurrent indicators that indicate south to north transport; however, the few localities that contain abundant silicic volcanic clasts have pebble imbrication suggestive of east to west and southeast to northwest transport. This transport data, and the fact that the Simmler fines to the northwest suggest that its principal source was to the south or southeast. An exposure of banded biotite gneiss, biotite granodiorite, and quartz monzonite occurs under the Caliente Formation just to the south across the Blue Rock fault, south of which the Simmler Formation, underlying Pattiway Formation, and overlying Vaqueros Formation are missing. This area could have been a highland of basement rocks that supplied detritus to the Simmler Formation. The silicic volcanic clast suite may have been derived from the e t across the San Andreas fault.

In the eastern Caliente Range (fig. no. 2), the Simmler Formation consists f arkose and siltstone with only minor conglomerate like that in the Cuyama badlands. Current lineations on sandstone beds are consistent with south t north and southeast to northwest curre flow.

Sespe Formation

On upper Sespe Creek (fig. 1, no. 5 conglomerates of the Sespe Formation h e clasts of coarse-grained arkose, mediu grained muscovite-biotite quartz monzo ite, a variety of recrystallized dacit



ormon, (1964).
ahns, (1940).
rowell and Susuki, (1959).

Figure 2.--Correlation chart showing the relative ages of studied sections and age ranges of dated basalt samples. Line pattern in series column indicates zone of controversy of series boundaries; stippled pattern indicates nondeposition or erosion. UN, unnamed rocks.

rhyodacites, rare anorthosite (plagio-
e AN25), and mafic volcanics. Pebble
ication shows clast transport from the
h across the Big Pine and Pine Mountain
ts. It is possible that the crystal-
clasts were derived from the highland
he Cuyama badlands area, and the
se from Eocene sandstone exposures to
north; however, neither area is known
ontain anorthosite or mafic volcanics.
s also possible that the Nacimiento
conada) and Pine Mountain faults were
ne time continuous and that right
ke-slip occurred on them (T. W. Dibblee,
onal commun., 1974). If so, the
e would have been deposited southeast
he present outcrop area and could
received detritus from the Alamo
tain area or from across the San
iel fault.
n Canton Canyon the Sespe Formation
. 1, no. 6) is coarse conglomerate,
cia, and immature sandstone with
ts of anorthosite (plagioclase AN 45-50),

amphibolite, banded augite-biotite gneiss, biotite-hornblende syenite, pyroxene gabbro, quartz syenite, norite, and unmistakable 220-m.y.-old Lowe Granodiorite of Miller, 1946 (a biotite monzonite, syenite, and granodiorite that is commonly sheared and contains garnet and large potassium feldspar phenocrysts). Pebble imbrication data suggest west to east transport from across the San Gabriel fault. Outcrops of anorthosite and related rocks occur in the western San Gabriel Mountains to the east; however, the large size of clasts (up to 7 m) indicates a high relief source close by. Right slip of about 60 km is required on the San Gabriel fault to juxtapose the Sespe in Canton Canyon to the anorthosite-Lowe Granodiorite source in the San Gabriel Mountains (Crowell, 1954).

Plush Ranch Formation of Carman (1964)

In Lockwood Valley (fig. 1, no. 4), the Plush Ranch Formation of Carman (1964) contains three conglomeratic members. One, at the base of the formation (member 1 of Carman, 1964), has clasts of medium-grained biotite quartz monzonite, banded pyroxene-biotite gneiss, coarse- to medium-grained syenite, and rare biotite-rich augen and porphyroblastic gneiss like that gneiss cropping out on Frazier Mountain to the southeast of locality 4. Pebble imbrication data in this conglomerate unit are ambiguous, with transport both from the northwest and from due south. Overlying this lower conglomerate is a sequence of interbedded arkose and siltstone (members 2 and 3 of Carman, 1964) that contains, near its top, large coarse lenses of monolithologic breccia with clasts of coarse-grained biotite granite identical with the Jurassic(?) Mount Pinos Granite of Carman (1964) exposed a few kilometres to the north. Near the top of the Plush Ranch Formation, conglomerate and breccia of member 5 (Carman, 1964) occur in a thick and long, but narrow, unit along the Big Pine fault. The large clasts within the unit include biotite-rich augen, porphyroblastic gneiss, and medium-grained biotite quartz monzonite. Pebble imbrication data (Kahle, 1966; this report) show transport from south to north.

The lower conglomerate of the Plush Ranch possibly had different sources. Clast lithologies such as augen gneiss and syenite relate to southerly source areas on Frazier Mountain and possibly to the Soledad basin, while granitic gneiss and quartz monzonite are like rocks found several km to the north on Mount Pinos. The breccia lenses must have been derived from the area of Mount Pinos, because their coarse, poorly sorted, massive texture suggests that they originated as landslides off a high, nearby source and their clast lithology is identical to that of the Mount Pinos Granite. The breccia along the Big Pine fault has clasts that suggest a source in the augen-gneiss terrain of Frazier Mountain. Their massive, poorly sorted character and coarse clasts indicate that the source was nearby and had considerable relief; however, Frazier Mountain is about 12-km southeast, across the Big Pine faul which suggests possible strike slip on that fault. Hill and Dibblee (1953), Poynor (1960), and Crowell (1968) pres additional data to support the claim f 14 km of left slip on the Big Pine fau and Crowell (1968) suggested that it h a two-stage displacement history that involved dip slip in the mid-Tertiary and later strike slip in the Quaternar

Vasquez Formation

In the Soledad basin the Vasquez Fo mation occurs in three separate outcro areas--Charlie Canyon (fig. 1, no. 7), Texas Canyon (no. 8), and Vasquez Rock (no. 9).

The Charlie Canyon section is mostl sandstone and siltstone at its base, b coarsens upward and is conglomeratic about mid-section. This conglomerate and associated shale chip breccias occ in beds and lenses at the top of a san stone unit and contain (2-10 cm) clast predominantly of coarse- to medium-grained arkose, medium-grained muscovi- biotite quartz monzonite, and hornblen- biotite quartz diorite, and some bande garnet-biotite gneiss. Higher in the section, conglomerate is the predomina lithology; quartz diorite clasts incre in percentage to the top of the sectio where there is a coarse monolithologic breccia of them with clasts as large a 5 m. Paleocurrent features are scarce in the lower, finer grained units in t Charlie Canyon section but are excelle in the higher and coarser units. Pebb imbrication data show transport from t east to west about mid-section, with a uniform shift to transport from nearly south to north at the top of the secti

The paleocurrent data in the Charli Canyon Vasquez Formation suggest an easterly to southerly source area and the large size of many clasts indicate that it was nearby; however, the only exposures for some distance east and southeast, across the San Francisquit fault (fig. 3), are of the Cretaceous Pelona Schist, a distinctive greensch t does not occur as clasts in the lie Canyon section. Konigsberg (1967) osed that granitic, high-grade meta- nic and sedimentary rocks tectonically ed the Pelona Schist, but were eroded as the Sierra Pelona anticline (fig. 3) , leaving a core of Pelona Schist ex- d. Tectonic capping of the Pelona st can be demonstrated on the southeast of Sierra Pelona Ridge, where green- st is overlain by granitic rocks on a of mylonite.

ne Vasquez Formation in Texas Canyon redominantly conglomerate, which nyi (1966) subdivided on the basis of t type and matrix color. The Pelona Vasquez Canyon faults bound the north- and southeast sides of the Texas on basin, respectively, and both faults k locally derived breccias. On the hwest side the formation contains cia of foliated medium-grained quartz onite, and on the southeast side, a se biotite-rich augen-gneiss breccia, of which are faulted against basement types similar to their clasts. Con- erate in the central part of the basin, in the section, has clasts of pilo- tic basalt (plagioclase, An60) with nsive alteration to calcite, banded et-muscovite-biotite gneiss, and -banded rhyolite. This conglomerate ains fragments of coarse-grained ite granite but none of basalt near top of the section. There is also a lomerate unit at the top of the ion on the east side of the basin contains clasts of coarse-grained thosite, diorite, gabbro, Lowe Grano- ite, syenite, augen gneiss, and red red andesite.

lthough paleocurrent indicators are in the Texas Canyon rocks, the vation of many of the units is obvious. ts in the breccias that flank the n match adjacent basement rock lithol- s and were probably locally derived dip-slip fault scarps of the Pelona Vasquez Canyon faults (fig. 3). The thosite conglomerate bears clast ologies like basement rocks of the ern San Gabriel Mountains and of the uez Formation volcanic sequence near western San Gabriels, and thus probably originated in that area.

If so, the alluvial fan represented by this detritus must have spread across deposits of the Vasquez Formation at Vasquez Rocks; hence, the Texas Canyon and Vasquez Rocks basins must have been joined at that time. It is not clear where the source for the basalt clasts in the lower part of the section was, however, as there are no known occurrences of similar basalt in the area. The basalt in the Vasquez Rocks area does not have the extensive calcite alteration nor the dense plagioclase lath concentration of these clasts, and thus does not offer a likely source. It is possible the clasts were derived from northeast across the San Andreas fault.

The Vasquez Formation at Vasquez Rocks has two distinct conglomerate clast suites. One at the base and top of the section contains clasts of coarse-grained anorthosite, biotite-hornblende gabbro, medium-grained syenite, and banded biotite gneiss. In the middle of the section a unit of crossbedded sandstone and breccia lenses contains large clasts of epidote-rich Lowe Granodiorite and basalt similar to the Vasquez basalts.

Pebble imbrication in the upper conglomerate indicates transport from the south, across the Soledad fault (fig. 3), and the anorthosite terrain there matches the clast lithology. These data suggest that the Soledad fault was active as a dip-slip fault during Vasquez deposition. Paleocurrent data are absent in the granodiorite-bearing breccias (Lowe); however, the unique lithology of the Lowe makes it easily relatable to a source. Nearby outcrops of epidote-rich Lowe occur due east and northeast of the breccias. Vasquez basalts, which are stratigraphically lower than the Lowe-bearing breccias, occur in this source area in patches. This area, then, probably provided the source for these breccias.

Very little, if any, of the Vasquez Rocks section appears to have been derived from the west, as arkose, siltstone, and borates are faulted against gneiss there and conglomerates in that area bear anorthosite clasts from the southeast.

Formation of Diligencia

Several conglomeratic units occur in the formation of Diligencia in the Orocopia Mountains (fig. 1, no. 10). Lenticular conglomerate beds at the base of the section contain pebbles and cobbles of banded muscovite-biotite gneiss, of medium-grained biotite quartz monzonite, and of granodiorite. Higher in the section, interbedded with a lakebed sequence of arkose, siltstone, limestone, and borates, there are a few massive beds of poorly sorted conglomerate with pebbles and small cobbles of anorthosite, gabbro, and possible Lowe Granodiorite. In the upper part of the section, exposed in the western part of the formation, a coarse conglomerate contains clasts of medium-grained syenite, pilotaxitic basalt of the same lithology and texture as the basalt clasts found in the Vasquez Formation in Texas Canyon, and less commonly augen gneiss. Coarse unsorted breccia lenses having clasts of coarse-grained biotite granite occur interstratified with this conglomerate.

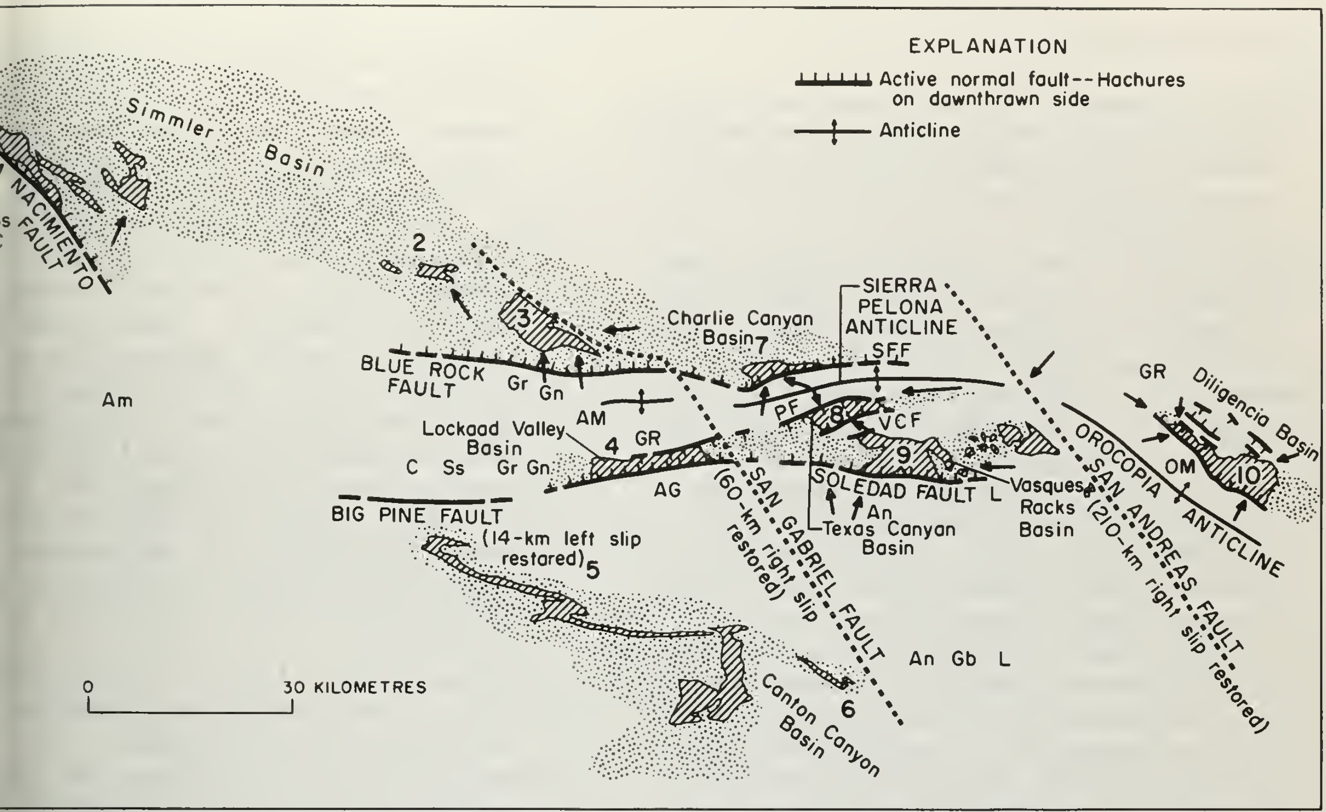
Basement rock exposures north and east of the Orocopia Mountains consist of quartz monzonite, granodiorite, and gneiss that probably provided the source for the conglomerate at the base of the formation of Diligencia. Just south of the Diligencia exposures, across the Clemens Well fault (fig. 1), outcrops of anorthosite, gabbro, and syenite could have provided the detritus to the thin, but massive conglomerate beds interstratified with the lakebed sequence. The granite breccias in the upper part of the section probably had their source immediately to the north where granite crops out today. The large basalt clasts, however, are unlike any rocks presently exposed in the nearby area. They are coarsest in the west and fine to the east and southeast, which suggests a westerly source that could possibly be either eroded or buried under clastic sediments in the Mecca Hills (fig. 1). Using the following palinspastic reconstruction, the Mecca Hills area could also provide the source for the similar basalt clasts in the Texas Canyon area.

PALINSPASTIC RECONSTRUCTION

Crowell (1962, 1968), Ehlig and Ehl[illegible] (1972), Carman (1964), Poynor (1960), Kahle (1966), and Sage (1973) have out[illegible]lined evidence suggesting that 210 km right slip has occurred on the San And[illegible]as fault, 60 km right slip on the San Gab[illegible]el fault, and 14 km left slip on the Big [illegible]ne fault since the Miocene. By making pa[illegible]n-spastic adjustments to account for the[illegible] amounts of slip, a diagram such as fig[illegible]e 3 can be constructed. Figure 3 shows [illegible] proposed distribution of basins that r[illegible] ceived sediment in the mid-Tertiary. [illegible]is diagram can be constructed because the total documented slip on the faults in[illegible]volved appears to have taken place aft[illegible] deposition in the basins involved. Al[illegible], I believe that the resultant basement [illegible]ck and source area distribution fits best with observed sedimentologic data gath[illegible]ed in this study.

Faults thought to have been active [illegible] normal sense during the mid-Tertiary a[illegible] shown as hachured lines, present-day o[illegible]-crops of mid-Tertiary rocks are shown [illegible] a lined pattern, and other areas thoug[illegible] to have received continental sediment [illegible] are shown stippled on figure 3. With [illegible] configuration, the Pelona Schist expos[illegible] on Abel Mountain and Sierra Pelona Rid[illegible], and the exposures of the Precambrian Orocopia Schist of Miller (1944) in th[illegible] Orocopia Mountains, as well as the cor[illegible]s-ponding Sierra Pelona and Orocopia ant[illegible] clines, appear to line up as one major[illegible] east-west trending feature. This structure, which must have been formin[illegible] in the mid-Tertiary but had not yet ex[illegible]posed schist, is flanked on the north [illegible] northeast by the Blue Rock-San Francisquito faults, and the Simmler, Charlie Canyon, and Diligencia basins. The Simmler and Charlie Canyon section[illegible] are very similar, suggesting that they were deposited in an interconnected basin.

On the south, the Sierra Pelona-Orocopia anticlines are flanked by com[illegible] faults and basins, which include the [illegible] Pine and Soledad faults, and the Lockw[illegible] Valley, Texas Canyon, and Vasquez Rock[illegible] basins. Granite, which occurs in outc[illegible]



ure 3.--Map showing proposed distribution of mid-Tertiary basins after palinspastic restoration of slip on the San Andreas, San Gabriel, and Big Pine faults. Arrows indicate transport directions; stipple indicates inferred depositional areas of basins. Ss, sandstone; C, conglomerate; Gr, granitic; GR, granite; Gn, gneiss; AG, augen gneiss; An, anorthosite; Gb, gabbro; L, Lowe Granodiorite; SFF, San Francisquito fault; VCF, Vasquez Canyon fault; PF, Pelona fault; AM, Abel Mountain; OM, Orocopia Mtns. of Miller (1946). Numbered areas refer to fig. 1. Lined pattern indicates present outcrop areas.

of the Lockwood Valley and Orocopia s, occurs in the Plush Ranch, Texas n, and Vasquez Formations, and the tion of Diligencia in an east-west te province that apparently crosses ierra Pelona-Orocopia anticlinal re. Augen-gneiss exposures and clasts occur south of the Big Pine fault, en the Texas Canyon and Vasquez Rocks s and south of the Orocopia basin, do ise. Anorthosite gabbro and assoc- rocks occur adjacent to the Canton n, Vasquez Rocks, and Diligencia s, which received detritus from them. us, the mid-Tertiary in southern ornia appears dominated by east-west tural trends, which include normal s and associated basins and uplifts n actively forming and rising anticlinal feature. The San Andreas and San Gabriel faults do not appear to have been active during that time, but subsequent right-slip movements on these fault zones have displaced these features to their present positions.

ACKNOWLEDGMENTS

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OFFSET OF THE UPPER MIOCENE CALIENTE AND MINT CANYON FORMATIONS ALONG THE SAN GABRIEL AND SAN ANDREAS FAULTS

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ACT

unique rapakivi-textured quartz
e porphyry and quartz monzonite por-
occur in a Tertiary volcanic complex
e northern Chocolate Mountains north-
of the San Andreas fault. Identical
yries occur as clasts in both the
ne Mint Canyon Formation of Soledad
southwest of the San Andreas fault
he Miocene Caliente Formation of the
ood Valley - Quatal Canyon area west
e San Gabriel fault.

position of the Mint Canyon Formation
red within a broad westward draining
h which crossed the San Andreas fault
Soledad Pass. Conglomerate along the
h axis consists mainly of volcanic
s, derived from the Chocolate Mountain
nic complex, which include a small
ntage of the unique quartz latite
yry. Clasts in the northern and
ern margins of the formation consist
minantly of locally derived basement
types. Conglomerates of the Caliente
tion contain the same clast assemblage
curs in the Mint Canyon Formation.

he Mint Canyon Formation is offset
the rapakivi source area by about 150
of right slip along the San Andreas
and the Caliente formation is offset
the Mint Canyon Formation by about
miles of right slip along the San
el fault, giving a total displacement
5-190 miles along this part of the
ndreas system. This displacement is
ame as that shown by pre-Cenozoic
ent rocks. Since the youngest parts
e offset formations are about 12 m.y.
the maximum age of this part of the
ndreas fault system is no greater
12 m.y.

INTRODUCTION

The Mint Canyon Formation, described by Jahns (1940) and Oakeshott (1958), crops out in the Soledad Basin, 30 miles north of Los Angeles, and is situated between the San Gabriel and San Andreas faults, being truncated on the southwest by the San Gabriel fault. The Caliente Formation is widely exposed to the west of the San Andreas fault in the region southwest of Bakersfield. The part of the Caliente Formation referred to here, described by Carman (1964), crops out in the Lockwood Valley - Quatal Canyon area, directly west of the juncture of the San Gabriel and San Andreas faults. The Caliente Formation of the Caliente Range and Cuyama Valley area is described by Hill and others (1958). Both formations are of fluvial and lacustrine origin and contain vertebrate faunas spanning Medial Miocene to early Pliocene time (Jahns, 1940; James, 1963). Carman (1964, p. 42-43) concluded that the lower fluvial parts of the two formations were deposited in the same westward flowing drainage system and later off-set along the San Gabriel fault by about 20 miles of right slip, as was also postulated elsewhere by Crowell (1952). This conclusion was based on the similarity of clasts in conglomerate within the two formations, including anorthosite clasts, whose only known source is in the western San Gabriel Mountains, and volcanic clasts, foreign to both areas and assumed to be from the general area of the present Mojave Desert.

Among the volcanic clasts which occur in the Mint Canyon and Caliente formations is a unique rapakive-textured quartz latite porphyry. The identical rock occurs in place within the northern Chocolate Mountains on the east side of the San Andreas fault near the Salton Sea (Ehlig

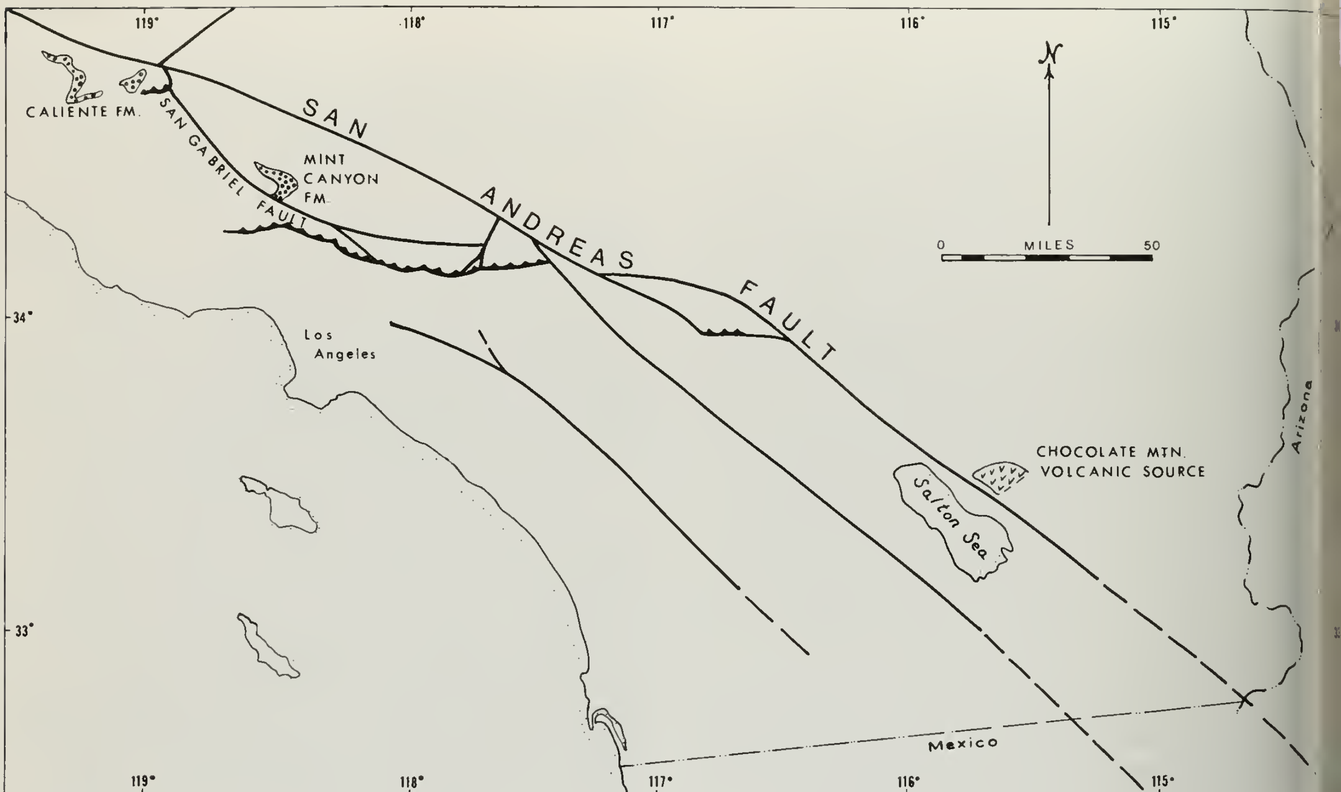
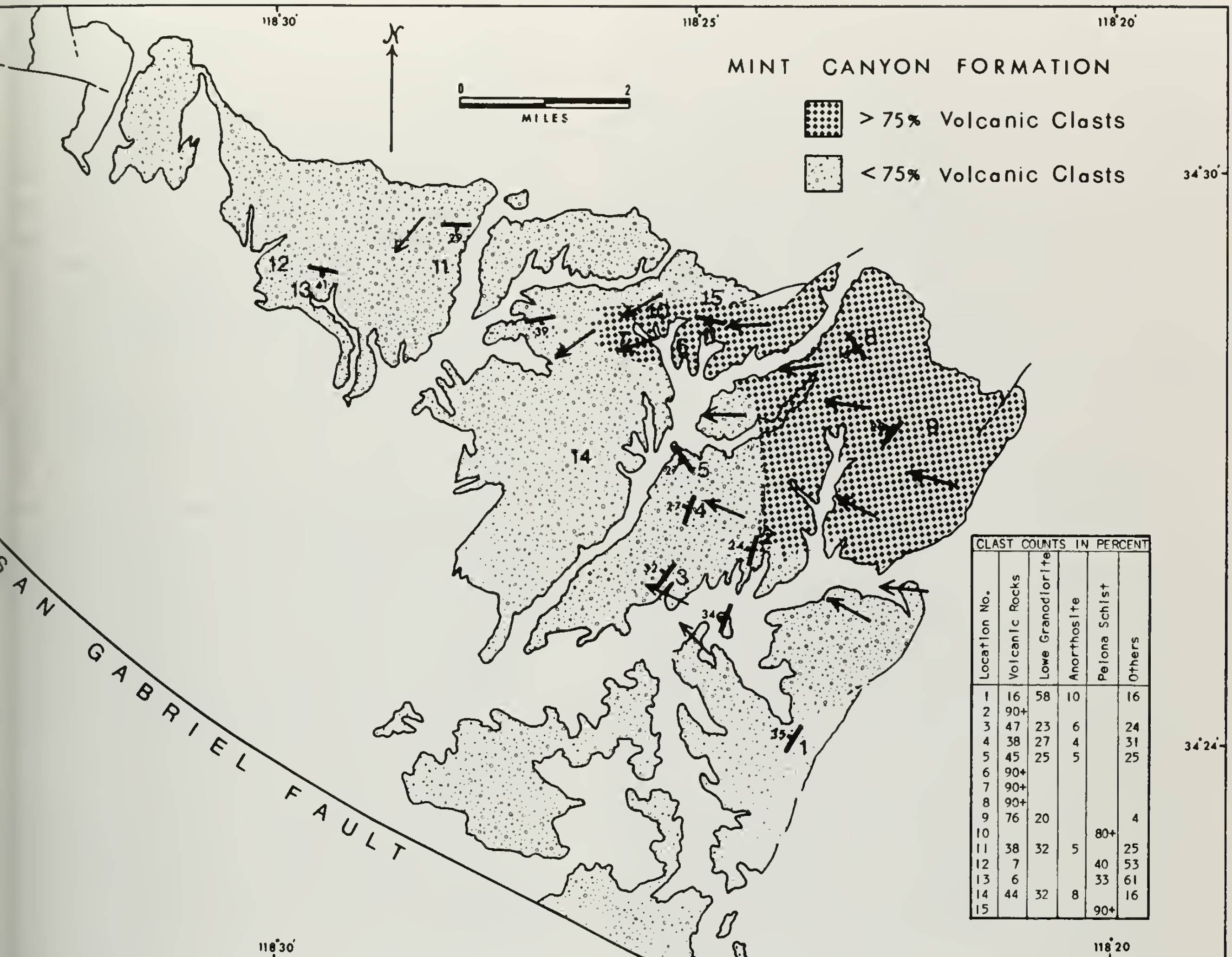


Figure 1.
Index map showing location of Mint Canyon Formation, Caliente Formation and Chocolate Mountain source terrane.

and Ehlert, 1972). Adjoining basement terrane in the Orocopia Mountains contains anorthosite, syenite, augen gneiss and Lowe Granodiorite identical in petrology, history and age to that of the Soledad Basin and western San Gabriel Mountains (Crowell and Walker, 1962; Silver, 1971). Other volcanic rocks strikingly similar to those found in both the Caliente and Mint Canyon Formations also occur in the northern Chocolate Mountains and are significantly different from other assemblages observed in volcanic terranes within the Mojave Desert. This, in combination with other findings summarized below, indicates Lockwood Valley and the Soledad Basin were located to the west of the northern Chocolate Mountains, near the present position of the Salton Sea, during Miocene deposition of the Caliente and Mint Canyon Formations.

DEPOSITIONAL ENVIRONMENT OF MINT CANY[ON] FORMATION

The Mint Canyon Formation crops ou[t] i[n] a broad southwestward plunging synclin[e] within the central and southwestern Soledad Basin (Fig. 2). In most plac[es] it overlies a small and variable thic[kness] of the Tick Canyon Formation which co[n]tains a late early Miocene vertebrate fauna significantly older than that f[ound] in the main body of the Mint Canyon F[orma]tion (Jahns, 1940, p. 169). The unconformity at the base of the combi[ned] Mint Canyon and Tick Canyon Formation[s] transects a mosaic of west to southwe[st] trending faults which were active bot[h] during and after deposition of the Oligocene - lower Miocene Vasquez For[ma]tion. Coarse locally derived conglom[erate] within the Tick Canyon Formation appe[ars] to fill canyons in a pre-existing to[pog]



CLAST COUNTS IN PERCENT

Location No.	Volcanic Rocks	Lowe Granodiorite	Anorthosite	Pelona Schist	Others
1	16	58	10		16
2	90+				
3	47	23	6		24
4	38	27	4		31
5	45	25	5		25
6	90+				
7	90+				
8	90+				
9	76	20			4
10				80+	
11	38	32	5		25
12	7			40	53
13	6			33	61
14	44	32	8		16
15				90+	

e 2.
p of the Mint Canyon Formation showing paleocurrent directions and clast type ibution.

of moderate relief. The upper part e formation includes much reddish tone and siltstone, perhaps reflect- he development of a broad valley of elief. Jahns, (1940, p. 162) con- s the contact between the Mint Canyon ick Canyon Formations as an uncon- ty; however, in the eastern part of rea the contact appears gradational. the transition is marked by a change largely locally derived sediments to omerate and conglomeratic sandstone ining abundant exotic volcanic clasts. the onset of Mint Canyon deposition cts an expansion of the area draining into the Soledad Basin.

The Mint Canyon Formation has an exposed thickness of about 6,000 feet along the axis of the Soledad Basin. Here it consists almost entirely of sandstone and conglomerate of fluvial origin. Strata exposed to the south and west are in large part of lacustrine origin. In the vicinity of Bouquet Canyon the exposed thickness is about 4,000 feet (Jahns, 1940, p. 162). Further northwest between San Francisquito and Elizabeth Lake Canyons, the Mint Canyon Formation is overlapped by the slightly younger marine Castaic Formation.

The northwestward thinning of the Mint Canyon Formation is partly the result of erosion prior to deposition of the Castaic Formation but also reflects original thinning toward the northern margin of the basin in which the Mint Canyon Formation was deposited. Paleocurrent measurements obtained within the fluvial part of the Mint Canyon Formation indicate current flow was essentially from east to west (see Fig. 2). The majority of the paleocurrent measurements were taken from scour and fill channels along with imbricate pebbles and cobbles.

Clast counts were made at numerous locations within the Mint Canyon Formation. A few representative ones are shown in Fig. 2. Clasts in the northern and southern margins of the formation consist predominantly of locally derived basement rock types, while clasts in the central part are dominantly of volcanic origin. The area shown in heavy pattern contains greater than 75 percent volcanic clasts, and much of this area contains over 90 percent volcanic clasts imbedded in a volcaniclastic matrix. The volcanic clasts are as much as 3 feet in diameter and are angular to subrounded. Although a small fraction of the Mint Canyon clasts appear to have come from the nearby Vasquez volcanics, most are foreign to the area and must have been derived from east of the San Andreas fault.

Included among the wide variety of volcanic clast types is a unique rapakivi-textured quartz latite porphyry; this rarely exceeds 5 percent of the total clasts.

We interpret the volcanic conglomerate to have been deposited along the axis of a broad alluvial wash. A modern analogy might be Salton Wash between the Orocopia and Chocolate Mountains.

The source areas of locally derived conglomerates place constraints on where the alluvial wash crossed the San Andreas fault. South of the volcanic conglomerate Lowe Granodiorite is the dominant cla
type. The biotite-bearing facies of
Granodiorite is particularly abundant
The occurrence of biotite-bearing Low
Granodiorite basement is restricted t
northwestern San Gabriel Mountains ju
east of Soledad Pass. The main alluv
wash could not have crossed the San
Andreas much further east than the pr
position of Soledad Pass. Anorthosit
clasts are also common in the souther
area but are generally only a fourth
fifth as abundant as Lowe Granodiorit
This suggests that the anorthosite te
of the western San Gabriel Mountains
either largely buried beneath an allu
cover or was an area of very low reli
Volcanic clasts occur in the southern
but are much less abundant than in th
central region and include a high pro
tion of volcanic types derived from t
Vasquez Formation. Vasquez volcanics
basement rocks in the Soledad Pass ar
today and probably capped basement ro
in a part of the western San Gabriel
Mountains during the Miocene.

Clasts along the northern margin o
Mint Canyon Formation are generally s
and consist of rock types exposed a s
distance to the north and northeast.
Clasts from the syenite and blue-quar
granite exposed along the west side o
Soledad Pass occur scattered among vo
canic clasts in the northeastern part
the volcanic conglomerate. West of M
Canyon, clasts of Pelona Schist are
abundant near the base of the formati
and locally form beds of monolitholog
breccia. Pelona Schist underlies Sie
Pelona to the north of the Soledad Ba
and the base of the Mint Canyon Forma
rests directly upon Pelona Schist bet
Bouquet and San Francisquito Canyon.
of Bouquet Canyon there are abundant
clasts of brown sandstone and rework
pebbles and cobbles from the Paleoce
Francisquito Formation which crops ou
west of Sierra Pelona. Thus, the
distribution of locally derived clast
requires the alluvial wash to have cr
the San Andreas fault in the general
vicinity of Soledad Pass.

ake deposits consisting of interbedded stone, siltstone and claystone nate the northwestern and southern sures of the Mint Canyon Formation. tracing of mappable beds indicates of the lake deposits are stratigra-ally higher than the volcanic lomerate. Their occurrence close to base of the formation in the north-ern and southern exposures is ibuted to onlapping of strata onto the n margin following deposition of the anic conglomerate along the axis of basin.

ENTE FORMATION

ne Caliente Formation crops out almost inuously in a northwest-southeast ction from Lockwood Valley to the cen-part of the Caliente Range, a distance bout 50 miles. Near the southern edge ockwood Valley it laps out against ment rocks and is overlain by the wood Clay (Carman, 1964, p. 38). In Caliente Range and to the south of na Valley it grades westward into the ne Branch Canyon Formation (Hill and rs, 1958, p. 2991). Thus, the ente Formation was deposited as a mont alluvial fan on a north-northwest ding coastal plain. Regional drainage have been essentially from east to .

onglomerate beds within the Caliente ation of the Lockwood Valley-Quatal on area contain clast types strikingly lar to those found in conglomerates of lower part of the Mint Canyon Formation. ts are generally smaller and more ded than in the Mint Canyon Formation, the suite of clast types is the same. ost places 50-75 percent of the clasts of volcanic origin. Included among volcanic clast types is the unique kivi-textured porphyry. Lowe odiorite comprises 10-20 percent of clasts within the southeastern part of area and is present in lesser amounts in the northwestern part of the area. thosite is widespread but probably does exceed 10 percent of the clasts at any tion. Clasts of Pelona Schist are common throughout the area and are locally abundant in Quatal Canyon. Other clast types include syenite and blue-quartz granite, brown sandstone - probably reworked from the Paleocene Francisquito Formation, and common types of granitic rock.

GEOLOGY OF THE CHOCOLATE MOUNTAIN SOURCE TERRANE

A mid-tertiary volcanic terrane containing the same hypabyssal and extrusive volcanic rock types as those that occur as clasts in the Mint Canyon Formation, including the rapakivi-textured porphyry, is located 150 miles southeast of the Mint Canyon Formation in the northern Chocolate Mountains, east of the San Andreas fault. Rapakivi-textured rocks occur at several locations within the range but the unique rapakivi-textured quartz latite porphyry found as clasts in the Mint Canyon and Caliente Formations is limited to the northern Chocolate Mountains. A pluton of several square miles consisting of rapakivi-textured quartz monzonite porphyry occurs along the western margin of the range southeast of Salton Wash. The pluton is cut by a myriad of steeply inclined northwest-trending dikes varying from rhyolite to andesite in composition. Northeast of the pluton rapakivi-textured dikes intrude older crystalline rocks. These dikes are probably offshoots of the pluton. The dikes are commonly ten to twenty feet thick, steeply inclined, and north to northwest trending. Red colored rapakivi-textured extrusive rocks have not been found in place but occur in alluvial terraces along the northern edge of the Chocolate Mountains.

Other types of volcanic rocks in this area include andesitic to rhyolitic dikes in part related to small plutons and intermediate to silicic flows, domes, and ignimbrites that crop out primarily in the eastern part of the range. During the Miocene, the volcanic cover was probably much more extensive than today.

DESCRIPTION OF RAPAKIVI TEXTURED ROCKS

The unique rapakivi-textured rocks which occur in outcrop within the northern Chocolate Mountains and as clasts in the Caliente and Mint Canyon Formations are characterized by numerous phenocrysts of conspicuously mantled feldspar. The rocks fall into three groups: (1) light-colored quartz monzonite porphyry typical of the pluton in the northwesternmost Chocolate Mountains; (2) quartz latite porphyry with light-colored feldspar phenocrysts in a dark gray fine-grained to aphanitic groundmass typical of the dike rocks, and (3) red quartz latite porphyry of probable extrusive origin.

The most distinctive type is the dike rock in which feldspar phenocrysts constitute about a third of the rock and form stout single crystals and nearly equant glomeroporphyritic masses. The phenocrysts are generally 5 to 10 mm wide with some attaining 20 mm. The pinkish potash feldspar phenocrysts are typically mantled by a white rim of oligoclase about 1 mm wide with a few crystals containing andesine cores. Composite phenocrysts contain potash feldspar and plagioclase phenocrysts snowballed together and surrounded by a mantle of oligoclase. Some plagioclase phenocrysts contain abundant inclusions of biotite and show a complex growth history of zoning and re-sorption. In some of the rocks plagioclase is mantled by potash feldspar. Clots of fine-grained plagioclase, biotite, and hornblende are dispersed through most rocks. Some clots are partially rimmed by oligoclase. The dikes also contain small phenocrysts of quartz, biotite and horn-blende. The matrix is composed of very fine-grained quartz, feldspar and biotite. Granophyric and myrmekitic intergrowths are common. Reddish brown allanite is a minor accessory. Chemical analyses of six samples of this type of rock are shown in Table 1 (analyses CH-1, CH-2, MT-1, MT-2, CA-1 and CA-2). Dike rocks containing sparse phenocrysts also occur but are less abundant than the type described above. One sample from each area has been chemically analyzed (CH-3, MT-3, CA-3).

The rapakivi-textured quartz monzo porphyry is similar to the dike rocks described above except for a coarser grained matrix. Feldspar phenocrysts the same size as in the dike rocks, generally constitute 10 to 20 percent the rock. Biotite is oxidized to hema Some specimens contain small irregula shaped gas cavities. The single chem analysis of this type of rock (MT-5 i Table 1) indicates less SiO_2 and more Al_2O_3 than in the other rocks analyze This appears to be due to kaolinizati of feldspar in the matrix.

OTHER VOLCANIC ROCKS

In addition to rapakivi-textured rocks, exotic clasts within the Calie and Mint Canyon Formation include min olivine basalt and mafic andesite, abundant intermediate flow-rock varie ranging from porphyritic pyroxene and to hornblende dacite, abundant flow-b dacite to rhyolite, and biotite-sanid rhyolite. All of these rock types oc in the Chocolate Mountains. Some are present as hypabyssal intrusions with the range and the others occur in lav flows, domes and pyroclastic deposits along the northeastern flank of the r

DISCUSSION

Rapakivi-textured clasts in the Mi Canyon and Caliente Formations are so unique and so similar to rocks in the northern Chocolate Mountains as to le no doubt that the Chocolate Mountains their source. These rocks are unique to a combination of coexisting featur including abundance, size and shape o feldspar phenocrysts; the presence of mantled feldspars; other textural fea and variations in textures, and the p-sence of allanite as a minor accessor The suite of volcanic clasts in which rapakivi-textured rocks occur matches volcanic rocks within the Chocolate M tains but is different from assemblag found in other volcanic terranes in southern California.

TABLE I. CHEMICAL ANALYSES OF RAPAKIVI TEXTURED ROCKS

	CH-1	CH-2	CH-3	CH-4	CH-5	MT-1	MT-2	MT-3	MT-4	MT-5	CA-1	CA-2	CA-3
(wt %)													
O$_2$	69.29	67.11	69.87	71.08	75.28	70.05	69.22	69.19	68.42	68.01	71.87	70.43	72.25
O$_3$	14.65	15.76	14.94	15.30	13.66	14.36	14.54	15.88	15.49	17.51	14.55	14.58	13.89
O$_3$	3.71	4.35	3.09	1.95	0.11	3.45	3.13	2.97	3.94	2.80	2.20	2.88	2.68
O	0.58	0.65	0.89	0.37	0.11	0.59	0.47	0.77	0.50	0.37	0.41	0.47	0.49
O	1.06	1.31	1.52	1.04	0.63	1.19	1.18	1.50	1.02	1.33	1.02	0.89	1.01
O	4.16	4.18	4.24	4.04	4.05	4.12	4.27	4.30	3.98	3.87	4.01	3.91	3.83
O	4.23	4.05	3.23	4.42	4.61	4.26	4.31	3.92	4.12	3.74	4.25	4.18	4.42
O$_2$	0.51	0.51	0.50	0.42	0.37	0.51	0.50	0.51	0.48	0.52	0.49	0.51	0.47
O$_5$	0.10	0.14	0.09	0.12	0.11	0.10	0.10	0.13	0.11	0.11	0.13	0.09	0.11
O	0.08	0.09	0.08	0.05	0.05	0.08	0.06	0.08	0.05	0.05	0.05	0.06	0.05
(ppm)													
	170	130	119	170	184	161	164	114	178	125	184	172	190
	159	119	160	160	144	120	143	221	119	241	195	91	119

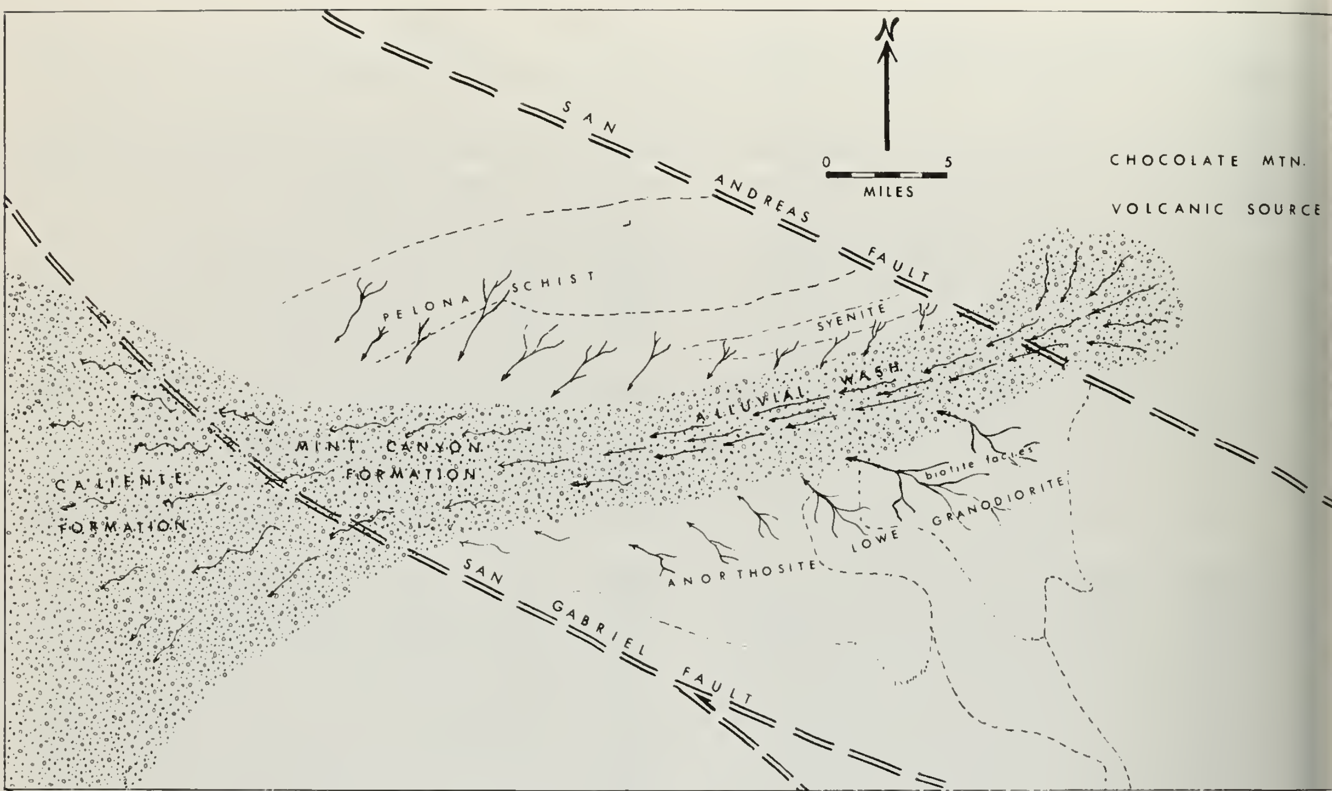


Figure 3.
Postulated drainage pattern during deposition of lower part of Mint Canyon and Caliente Formation before movement began along San Andreas and San Gabriel faults

The Mint Canyon Formation must have been deposited in close proximity to the Chocolate Mountains as inferred from the angularity of volcanic clasts and the absence of clasts from source areas other than the Chocolate Mountains and the region around Soledad Basin. Paleocurrent data and the distribution of locally derived clasts, particularly Lowe Granodiorite, indicate the Mint Canyon Formation was deposited in a westward draining trough which crossed the San Andreas fault in the vicinity of Soledad Pass. A minumum offset reconstruction would place Soledad Pass approximately opposite the mouth of Salton Wash during deposition of the Mint Canyon Formation and would require about 150 miles of right slip along the San Andreas fault since deposition of the Mint Canyon Formation.

The Caliente Formation of the Lock... Valley - Quatal Canyon area has the s... clast assemblage as the Mint Canyon F... mation, including clasts derived from pre-Miocene rocks on both sides of th... Soledad Basin and volcanic clasts fro... Chocolate Mountains. Since the two f... mations are the same age and contain ... same clast suite, they must have been deposited in the same trough and subsequently have been separated by righ... slip along the San Gabriel fault. A reasonable reconstruction indicates 3... 40 miles of offset.

The above offsets are the same as ... derived from correlation of basement ... across the San Gabriel and San Andrea... faults (Crowell, this vol.) and thus indicate faulting commenced after deposition of at least the lower half ... the Mint Canyon Formation and most of ...

iente Formation. Carman (1964, p. 42- notes that the upper part of the iente Formation is of local origin and have been deposited after the San riel fault began to move. The exten- e lake deposits within the upper half the Mint Canyon Formation were probably med after the Caliente Formation was off from the Soledad Basin. The lower t of the Mint Canyon Formation contains arstovian fauna and the upper part con- ns a Clarendonian fauna (Durham and ers, 1954, p. 66-67). The Caliente about the same age range (James, 1963). relations by Turner (1970, p. 112) place Barstovian - Clarendonian boundary at to 13 my. This is a maximum age for San Gabriel fault and is probably close its true age since marine rocks of nian age are offset only about 20 miles owell, 1952). Turner (1970) believes Mohnian stage occurred about 10 to 12 ago. The southern part of the San reas fault is probably younger than the Gabriel fault but how much younger is nown.

The offsets described above indicate a al displacement of 185-190 miles of ht slip along the southern half of the Andreas fault system within the past my.

NOWLEDGMENTS

We appreciate critical review of this er by Sean Carey and Robert Meade.

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BRINGING THE SAN ANDREAS FAULT INTO THE CLASSROOM

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RODUCTION

)ne of the principal difficulties in ping students to understand the San An-s fault stems from the sheer size of feature itself. Individual sites h visiting are miles apart and even a -day field trip will leave many stu-s confused as to the big picture; lack the background and perspective nst which each detail becomes an ex-ng enrichment of the whole concept.

)ne way to meet this problem is to sup-ent the field trips with visual aids bring the fault into the classroom. step in that direction the material follows is a preliminary assemblage films, slides, photographs and non-nical printed material dealing with San Andreas fault. All items listed been recommended by California geolo-s and are considered suitable for use junior high school, high school and ege levels, but the author's famili-y with the materials is very uneven.

1S (16 mm, color, sound)

he San Andreas Fault (21 minutes)

he fault trace as seen from the air on the ground; its effect on landscape rocks; model demonstrating stick-slip elastic rebound; evidence for cumu-ve displacement; association with hquakes; monitoring instrumentation.

roduced by: Encyclopaedia Britan-Educational Corporation; catalog 3304.

urchase from: EBEC, 425 North igan Avenue, Chicago, Ill. 60611. e: $255.00

Rent from: EBEC, 2494 Teagarden et, San Leandro, Calif. 94577 Fee: $11.00 plus shipping, for 1 to 3 days.

San Francisco: The City That Waits To Die (57 minutes)

A dramatic film that emphasizes earthquake hazards along the San Andreas fault, methods of coping with them, and the complacency of citizens and local government.

Produced by: BBC.

Rent from: Time-Life Films, 100 Eisenhower Drive, Paramus, N. J. 17652. Fee: $50.00 plus shipping for 2 days.

Earthquake I -- The Land (20 minutes)
Earthquake II -- The People (20 mins.)

These two films are based upon a TV program aired in February 1972 and narrated by Jules Bergman which examined the San Andreas Fault from south to north with the able assistance of Clarence Allen and other local experts.

Produced by: ABC TV.

Purchase from: Xerox Films, 245 Long Hill Road, Middletown, Conn. 06457. Price: $280.00. No rental.

The Earthquake Observatory (23 minutes)

How seismographs work; methods of locating earthquakes along the San Andreas fault and elsewhere.

Produced by: Prof. Bruce A. Bolt and colleagues, Univ. Calif. at Berkeley.

Available from: Director, Seismographic Station, University of California, Berkeley, Calif. 94720. Purchase: $312.00. Rental: $35.00 per day.

PHOTOGRAPHS AND SLIDES

Earth Resources Technology Satellite (ERTS) Images

A browse file (on microfilm) of these images is available for study at the U. S. Geological Survey, Topographic Branch, Building 3, 345 Middlefield Road, Menlo Park, Calif. 94025. Instructions for ordering prints may also be obtained here.

U-2 Photographs

High altitude verticals and obliques, in black-and-white, natural color, and infra-red color covering coastal belts and other sections of the U.S. Approximately 185,000 pictures on file. To make use of these send exact geographic coordinates of subject area to Earth Resources Aircraft Project, Ames Research Center, Mail Stop 211-12, Moffett Field, Calif. 94035, or call (415) 965-6252. Computer will print out (free) full information on all available photos of the area (date, kind of film, scale, etc.). Or, visit Ames Research Center and use their microfilm browse file. The selected photos may be ordered, on special forms provided for the purpose, from Sioux Falls, S.D. Cost depends on size etc.

U. S. Geological Survey Photographs

Copy negatives of many of G. K. Gilbert's photographs, most of the Branner collection, and original black-and-white and color photography by currently active geologists (including much of Robert Wallace's collection) are on file at the Photo Library of the U. S. Geological Survey, 345 Middlefield Road, Menlo Park Calif. 94025; telephone (415) 323-8111. Descriptions of available material on request.

California Division of Mines and Geology Photographs

Over 5,000 black-and-white photographs and some color slides of California geology and mining are on file in Sacramento. The black-and-whites are numbered, cross-referenced by subject, and filed in notebooks. The transparencies are catalog d by subject. Browsing by appointment o y For further information contact: Cali Div. Mines and Geol., Geologic Data Gr p 1416 Ninth Street, Room 1341, Sacramen , Calif. 95814. Telephone: (916) 445-0 4

Slide Set

Set of forty 35 mm slides entitled "Surface Features of the San Andreas Fault" includes views from U-2 flights aerial obliques, and ground shots, wit accompanying illustrated text. Produc by: Pilot Rock, Inc., 1551 G St., Arc a Calif. 95521. Distributed by: Geop , Tualatin, Ore. 97062. Price: $48.50 p set.

Shelton Photographs

Many views of the San Andreas fault (and other geologic features in the We) Mostly low aerial obliques, but also m y ground shots. Black-and-white and col . Available from: John S. Shelton, P. O Box 48, La Jolla, Calif. 92037.

NON-TECHNICAL PRINTED MATERIALS

Earthquake Country, by Robert Iacc . (Lane Book Co., Menlo Park, Calif. 196 ; 2nd ed. 1971.) Good popular account c relation between faults and earthquake in California. Maps, photos and descr - tions of San Andreas fault trace from Imperial Valley to Point Arena--a help l guide to finding the fault from Califo roads and highways.

The Earth Shook, the Sky Burned, b William Bronson. (Doubleday and Co., Garden City, N. Y., 1959). Notable f reproduction of over 400 on-the-scene photographs assembled from many histo ca collections and documenting nearly al as pects of the San Francisco earthquake n fire of April 1906. Text includes qu tations from contemporaneous publicat n and eye-witnesses.

Peace of Mind in Earthquake Countr by Peter Yanev. (Chronicle Publishin Co., San Francisco, Calif. 1974.) A structural engineer looks at living w h

:hquake hazards.

Remember, too, that both the U. S. Geo-
cal Survey and the California Division
lines and Geology, whose addresses have
 given above, print a variety of pam-
ets and information sheets, some free
some at nominal cost, that deal with
San Andreas Fault and California earth-
es. Many authoritative articles ad-
ssed to non-technical readers have also
eared in the monthly publication
fornia Geology (formerly "Mineral
rmation Service") issued by the Calif.
of Mines and Geology, and in the
ntific American.

OWLEDGEMENTS

he author is indebted to many geolo-
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ions of material to include in this
ary. He would also welcome word from
who find significant ommissions here.

eviewed by John C. Crowell.

ECTION 2

exico to Cajon Pass

:o 2. Trace of Banning fault (south branch of San Andreas fault), starting in center foreground and crossing Whitewater Canyon, southern San Bernardino Mountains. Looking west. Note the vegetation in the canyon where the faulting has apparently brought subsurface water closer to the surface. J. S. Shelton Photograph No. 6835, 24 Nov. 1974, 6500 ft. elevation.

Photo 3. San Andreas fault zone, northeast of San Bernardino, looking northwest
Note trace of fault from mountain-facing scarp in foreground, along ba
of range through new housing development in the center of photograph,
toward Cajon Pass in the distance. Several branches of the fault form
prominent lineaments in the foothills. State Highway 30 between Highl
and Running Springs in canyon of right foreground. "See photo page 145
J. S. Shelton Photograph No. 6846, 24 Nov. 1974, 8500 ft. elevation.

EOLOGIC SKETCH OF THE OROCOPIA MOUNTAINS, SOUTHEASTERN CALIFORNIA

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RACT

he Orocopia Mountains lie adja- to the San Andreas fault to northeast of the Salton Sea. ment rocks within them include ambrian augen gneiss, migmatite, ss, anorthosite-syenite com- and Mesozoic granodiorite, ite, and quartz monzonite. The of the range consists of an form of greenschist-facies Oro- a Schist (Mesozoic ?) that cturally underlies the folded opia thrust. On the northeast, t 1460 m (4800 ft) of marine r and middle Eocene beds, com- ing the Maniobra Formation, lie n of a rugged Eocene shoreline. e beds are overlain unconform- by about 1500 m (5000 ft) of marine Diligencia Formation, ly of early Miocene age. In Mecca Hills to the west about m (5000 ft) of nonmarine sand- e, siltstone, and conglomerate titute the Mecca and Palm ng formations of Plio-Pleisto- age. The youngest sedimentary s include the Pleistocene illo Formation, a fanglomerate extends basinward toward the hwest. Volcanic rocks, pri- ly of middle and late Tertiary are of several petrographic s and ages.

he structural evolution of the opia Mountains region began metamorphic and intrusive ts involving Precambrian and zoic rocks. Many of these ment rocks constitute the fold- verriding plate of the Orocopia st, a major regional overthrust nknown displacement and probably ate Mesozoic or earliest Ceno- age. The unconformably over- lying Cenozoic sedimentary section is irregularly deformed. Near major faults, such as the San Andreas, even Pleistocene beds are strongly faulted and folded. Major associated faults of the San Andreas system are the Painted Canyon, Eagle Canyon, Hidden Springs, and Clemens Well. On the east, folds with an eastsoutheast trend in strata of the Maniobra and Diligencia formations are associated with a system of vertical strike-slip faults; north-east striking faults have left slips and northwest striking ones, right slips.

INTRODUCTION

The Salton Trough is flanked on the northeast by the Orocopia Mountains and to the east by the Chocolate Mountains, two rugged desert ranges nearly barren of vegetation (Fig. 1). The Orocopia Mountains, lying between the Salton Sea and Salton Creek Wash on the south, and Interstate Highway 10 on the north, are fully accessible, but the Chocolate Mountains are part of the U.S. Naval Aerial Gunnery Range and are closed to public ac- cess. The Orocopia Mountains and its foothills on the west, the Mecca Hills, constitute the southeastern-most region covered in this guide-book. The region contains rock units of significance in understand-ing the displacement history of the San Andreas fault, as do the Choco-late Mountains further southeast-ward, because they are probably off-set from correlated units in the Soledad and Tejon regions to the northwest (Crowell, 1962). Only very recently, however, has geologic information from the Chocolate Mountains become available (Haxel and Dillon, 1973; Crowe, 1973; Haxel, 1974; Dillon and Haxel, 1975).

Early information on the geology of the Orocopia Mountains is found in papers by Mendenhall (1909), Brown (1923), Darton (1933), and Miller (1944). Dibblee (1954) mapped part of the region and applied several of the stratigraphic names now employed. Later published work includes that of Crowell (1957, 1960, 1962, 1973, 1974), Cole (1958), Crowell and Susuki (1959), Crowell and Walker (1962), Silver (1966, 1968, 1971), Ehlig (1968), Ehlig and Ehlert (1972), Armstrong and Suppe (1973), Woodburne and Whistler (1973), Spittler and Arthur (1973), and Spittler (1974).

The western part of the Orocopia Mountains, including the Mecca Hills, can be reached easily by hikes from conventional automobiles. Especially worthwhile are visits to view the rocks and structure 1) in the Painted Canyon area (Sylvester and Smith, this volume), 2) along Box Canyon (through which passes State Highway 195), 3) in the vicinity of Shaver Well, 4) in the Hidden Spring - Grotto region. The latter area is reached by trail from Box Canyon by way of Sheep Hole Oasis (see U.S.G.S. Mortmar Quadrangle). The northern flank of the Orocopia Mountains is accessible from several dirt roads leading up washes from Highway 195 and Interstate 10. Some of the most significant and scenic geology occurs in the eastern Orocopia Mountains, reached from the Coachella Canal road by way of rough and unimproved roads, sandy at places, along Salton Creek Wash. Here spectacular exposures of colorful sedimentary and volcanic rocks of the Diligencia Formation, deeply eroded into rugged canyons, are found in the vicinity of Canyon Spring and Red Canyon (U.S.G.S. Hayfield Quadrangle).

The rocks exposed within the Orocopia Mountains range in age from Precambrian to Recent, and are here described under three headings: 1) Basement rocks, including several types of gneiss, plutonic rocks of several sorts and ages, and schist, 2) Tertiary sedimentary rocks, including marine Eocene strata, Oligocene-Miocene nonmarine beds with associated volcanic rocks and younger sandstone and conglomerate, mainly of Plio-Pleistocene and Recent ages, and 3) other volcanic rocks.

The strucural history of the Orocopia Mountains is complex, involving deformation during the Precambrian and at several times during the Mesozoic. Major overthrusting, on the Orocopia thrust, took place in the late Mesozoic (?) and brought older metamorphic and granitic rocks above schist. Faulting and folding has occurred at intervals in the Cenozoic, and deformation is taking place today along strands of the San Andreas fault system.

BASEMENT ROCKS

Augen Gneiss and Migmatite

The oldest rocks so far recognized within the Orocopia Mountains are augen gneisses and migmatites exposed in the southeast near Salton Creek Wash, and north of the Clemens Well fault (Fig. 1), and are part of the Chuckwalla Complex (Miller, 1944). Characteristic of the unit are large, up to 8 cm, ovoid "eyes" of pink microcline within coarse-grained microfolded gneiss. The migmatite constitutes about 20 per cent of the augen-gneiss terrain and consists of intermixtures between impure feldspathic and quartz-rich gneiss, gneissic granite, and biotite schist. The augen geneiss has yielded a zircon age of 1670 ± 15 m.y. (Silver, 1971).

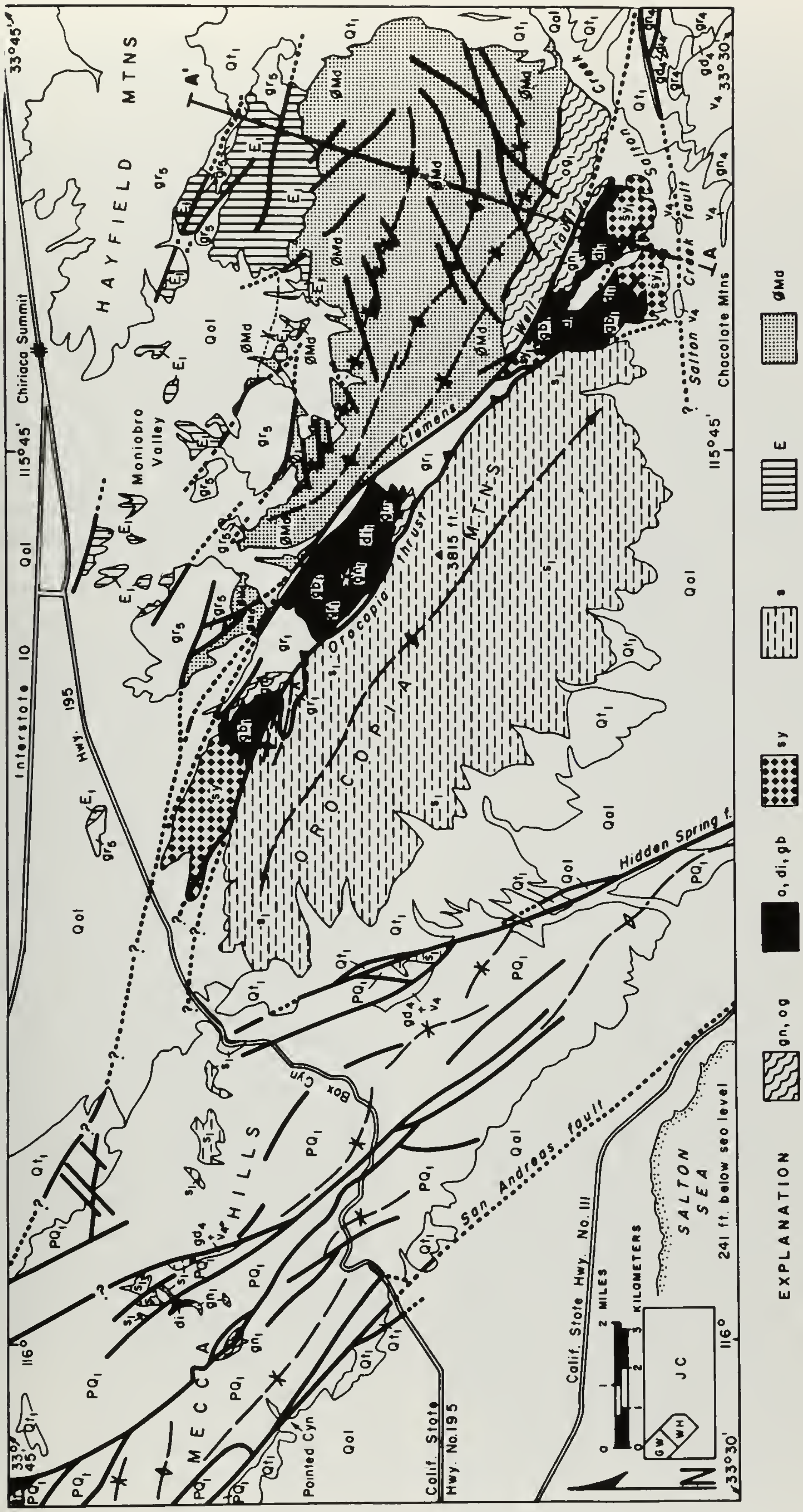
H A Y F I E L D   M T N S
O R O C O P I A   M T N S
M E C C A   H I L L S
SALTON SEA
241 ft. below sea level
Chiriaco Summit
Interstate 10
Hwy. 195
Moniobro Valley
Box Cyn
Painted Cyn
Calif. State Hwy. No.195
Calif. State Hwy. No. 111
San Andreas fault
Hidden Spring f.
Clemens Well fault
Orocopia thrust
Salton Creek fault
Chocolate Mtns
3815 ft.
2 MILES
KILOMETERS
EXPLANATION
gn, og
o, di, gb
sy
s
E
øMd

Figure 1. Geologic sketch map of the Orocopia Mountains, southeastern California. Subscript numbers serve to differentiate different rock units of similar types; see text of this paper and that of Crowell (1962). With reference to insert rectangle at lower left, the data are modified and simplified from unpublished mapping by Hays (WH) (1957), Ware (GS) (1958), and Crowell (JC). A-A' = Line of cross section of Figure 2. Precambrian rocks: gn = blue-quartz gneiss, ag = augen gneiss and migmatite, a = anorthosite, di = diorite, gb = gabbro, sy = syenite. Other pre-Tertiary basement rocks: gr = granitic rocks (several types), s = Orocopia Schist. Cenozoic rocks: v = volcanic rocks (several types), E = Eocene Maniobra Formation, ØMd = Oligocene - Lower Miocene Diligencia Formation, PQ = Plio-Pleistocene formations, Qt = Quaternary terrace and fanglomerate deposits, Qal = Quaternary alluvium and lake-bed deposits.

Blue-Quartz Gneiss and Gray Gneiss

Patches of gneiss crop out south and west of the Clemens Well fault, confined to the overriding plate of the Orocopia thrust, and also within hills flanking Maniobra Valley (Fig. 1). Banded gneiss, with an amphibolite-facies mineralogy, is intruded by rocks of the anorthosite-syenite group, and is characterized by quartz grains with a distinctive blue or violet color, and textures suggesting an earlier granulite-facies metamorphism. This gneiss has been dated at about 1425 m.y. by Silver (1971). Other areas of amphibolite-facies gneiss with gray quartz may or may not be of the same age. At places such gneiss occurs as isolated bodies or septa within Mesozoic (?) granitic plutons, and may therefore be younger than the definitely Precambrian gneiss. Blue-quartz gneiss is best exposed on the north flank of the Orocopia Mountains, and gray gneiss in deep gorges tributary to Painted Canyon, in the Hayfield Mountains, and in hills southwest of Maniobra Valley (Fig. 1).

Anorthosite-Syenite Complex

Irregular masses of rock belonging to an anorthosite group and closely associated with those belonging to a syenite group crop out in the overriding plate of the Orocopia thrust (Fig. 1) (Crowell and Walker, 1962). These complicated, deformed, and shattered rocks are especially well exposed north of Salton Creek Wash and along ridges just north of the crest of the Orocopia Mountains. A few small outcrops of anorthosite and related rocks crop out in Painted Canyon and are the most easily visited exposures of these types in the region (Sylvester and Smith, this volume). The anorthosite group consists of gabbro, diorite, transitional rock between gabbro and diorite or transitional between gabbro and anorthosite, white anorthosite, mafic bodies, and basic dikes (Crowell and Walker, 1962). The plagioclase of the anorthosite is oligoclase-andesine (An_{28-45}). The closely associated syenite group consists of syenite, quartz-bearing syenite, alkali granite, granophyre, and pegmatite. Blue or violet quartz, microperthite, and replacement textures of biotite after original mafic minerals are characteristic. Because the anorthosite and syenite groups are intimately associated, they are probaby related in origin. Their isotopic age is about 1220 m.y. (Silver, 1971) in origin.

Lowe (?) Granodiorite

Porphyritic granodiorite occurs in a few small outcrops just south of the mapped area near A of the ss-section line (Fig. 1, A-A') hin the northern Chocolate Mounns. The rock is medium-to rse-grained and faintly foliated, h characteristic large orthoclase nocrysts and smaller and irregully distributed hornblende phenosts. Quartz constitutes less n 10 per cent. On the basis of rographic similarity this granorite is tentatively correlated h the Lowe Granodiorite of the Gabriel Mountains which has been ed at 220 ± 10 m.y. (earliest assic) by Silver (1971). Simi- rock has recently been discoverby John Dillon in the south-cenl Chocolate Mountains, near Mamh Wash (personal comun., 1974).

nitic Rocks

Light-colored granitic rocks inde the gneisses and rocks of the rthosite-syenite complex in the copia thrust-plate. The main nitic rock is a fine-to mediumined leuco-quartz monzonite with plicated migmatitic borders. In t, there are several involved cts of "double migmatites" where er migmatitic borders of the rthosite - syenite complex and ient gneisses are cross-cut and matized by quartz monzonite. nite and quartz monzonite also erlie the Hayfield Mountains. se rocks, as well as those of the ckwalla and Little Chuckwalla ntains to the east, have yielded r ages between 71 and 88 m.y. mstrong and Suppe, 1973), sugting that cooling, perhaps the ult of uplift and deep erosion, k place during late Cretaceous e. Within the Orocopia Mountain ion it is not yet known how many ferent granitic plutons are pret, nor how diverse their ages. se granitic rocks on the northt constitute the basement floor n which the marine Eocene strata the Maniobra Formation were deited.

Orocopia Schist

The central part of the Orocopia Mountains is underlain by a 2000 m (6500 ft) sequence of greenschist-facies schist reconstituted metamorphically from graywacke and mudstone, with minor amounts of chert and basic volcanic rocks. The bedded schist, predominately gray in color, is mainly composed of quartz, albite, and muscovite with minor amounts of chlorite, epidote, actinolite, and graphite. Lithologic layering, derived from sedimentary bedding, is conspicuous in almost all outcrops, but scattered isoclinal-fold hinges suggest that some of the original bedding is transposed. Although the age and environment of deposition of the original sediments and volcanics now constituting the schist are unknown, it is noteworthy that none of the granitic plutons intrude the schist, and that nowhere are rocks visible beneath the schist. These relations suggest that perhaps the strata are younger than plutonism and metamorphism, or that they were deposited on oceanic-or quasi-oceanic floor so that no sialic sources for quartz monzonite plutons lay beneath them. The age of the metamorphism of the Orocopia Schist is also unknown, but is probably Mesozoic by comparison with events involving the very similar Pelona Schist in the San Gabriel Mountains (Ehlig, 1968). The foliation of the schist in the Orocopia Mountains has been broadly folded after the emplacement of the overriding Orocopia thrust; in this regard also it is similar to the Pelona Schist and its overlying Vincent thrust. In the absence of detailed studies of the Orocopia Schist, and by relying heavily on regional correlations, I tentatively consider the age of the original strata as Mesozoic (undesignated more precisely) and the age of the metamorphism as late Cretaceous. Schist probably correlative with the

the Orocopia Schist also occurs from the central Chocolate Mountains southeastward into central Yuma County, Arizona.

CENOZOIC STRATA

Eocene Maniobra Formation

The oldest unmetamorphosed sedimentary rocks in the Orocopia Mountains consist of about 1460 m (4800 ft) of Eocene beds containing marine fossils and assigned to the Maniobra Formation (Crowell and Susuki, 1959). These brown shales, sandstones, conglomerates, and sedimentary breccias lie unconformably upon granitic basement in Maniobra Valley (Fig. 1). Coarse rocks were deposited along an ancient Eocene shoreline, or steep near-shore buttress unconformity, which is preserved along the southern base of the Hayfield Mountains. Here huge polished boulders and giant blocks have apparently tumbled from shoreline cliffs and ancient sea stacks. From this near-shore area the beds thicken and become finer grained toward the south and southwest, suggesting that the open sea, or at least a broad marine embayment, lay in that direction. The fauna, consisting of Foraminifera (including Discocyclinids), gastropods, and pelecypods, indicates an early and middle Eocene age (Cole, 1958; Crowell and Susuki, 1959; Johnston, 1961). These fossils, as well as the lithology of beds containing them, show many affinities with those of the north-central Transverse Ranges, across the San Andreas fault and between 220 and 280 km (135 to 175 mi) to the northwest (Kirkpatrick, 1958; Crowell and Susuki, 1959; Howell, this volume).

Oligocene - Lower Miocene Diligen- Formation

The Diligencia Formation, consisting of about 1500 m (nearly 5000 ft) of nonmarine conglomera[te], sandstone, mudstone, and interbe[d]ded volcanic flows and sills, un[der]lies a large region in the easte[rn] Orocopia Mountains. The formati[on] lies unconformably upon the Eoce[ne] Maniobra Formation on the north where it is characterized by a basal conglomerate largely compo[sed] of rounded granitic cobbles. On the south, the formation lies unconformably upon augen gneiss an[d] migmatite one kilometer southeas[t] of Canyon Spring (U.S.G.S. Hayfi[eld] Quadrangle).

Lithologically the formation [con]sists of red sandstone and maroo[n] mudstone with lesser thicknesses [of] well bedded calcareous yellow sa[nd]stone, dark gray limestone, thin[ly] bedded sequences of gypsum and o[ther] evaporites, and irregular lenses [of] sedimentary breccia including mo[no]lithologic mosaic breccias of gr[an]itic and gneissic debris. Facie[s] changes are pronounced within th[e] unit, and tentative interpretati[ons] indicate that it was deposited i[n] an intermontane valley with roug[hly] east-west orientation. The vall[ey] was at times occupied by a lake, which occasionally dried up so t[hat] evaporites were laid down. Coar[se] debris entered the valley from b[oth] the north and the southwest, as shown by facies changes and pale[o]current indicators. The volcani[c] rocks consist of dark purplish-brown vesicular basalt flows, an[d] pilotaxitic andesitic dikes and and greenish tuff beds up to 60 (2 ft) thick (Crowell, 1962; Spittler and Arthur, 1973; Spitt[ler] 1974).

The formation is here named formally Diligencia, a Spanish word for stagecoach. Canyon Spr[ing] was a watering place for horses the Butterfield Stage Route betw[een] Mecca and Ehrenberg in the late 1860's (Brown, 1923, p. 6). Unt[il a] few years ago the foundation of ge house still remained on the ks of Salton Creek Wash northeast m the mouth of Canyon Spring Can- . The type section for the Dili- cia Formation is here designated include the beds along a north- th cross section from the uncon- mity with augen gneiss at the e, beginning at a point 850 m 00 ft) S 75° E from Canyon Spring shown on U.S.G.S. Hayfield Quad- gle (in the northern part of Sec. T. 7 S., R. 13 E.). It is in- ded that the formation include only the beds along this north- th cross section, but those to east and west as well. Com- x structure, intermixed irregular canic masses, and marked facies nges within the sedimentary stra- preclude the establishment of a aight-forward stratigraphic col- at present. No younger and dis- ct formations are known to over- the Diligencia Formation in its ion of outcrop except for local ternary fan, terrace, and allu- l deposits.

The age of the Diligencia Forma- n depends on its stratigraphic ition, a single vertebrate-fos- find, and three K-Ar isotopic es from interbedded volcanic ks, one of which is unsuitable to large analytical uncertain- . These dates are 22.4 ± 2.9 20.1 ± 8.9 m.y. (Crowell, 1973, le 1) and 18.6 ± 1.9 m.y. ttler, 1974). Recently Wood- ne and Whistler (1973) have des- bed oreodont remains from a k quite likely fallen from a dstone bed about 365 m (1200 ft) ve the base of the section. and it 0.8 km (0.5 mi) north of Can- Spring. Woodburne and Whistler lude from their comparison of e vertebrate remains with others outhern California "that at t the upper half of the (Dili- ia Formation) is of late Ari- ean, or less possibly, early ngfordian age." From all of this I tentatively conclude that the formation is primarily of early Miocene age but with the lower part probably extending down into the Oligocene.

Upper Cenozoic Formations

Nonmarine conglomerate, sandstone, siltstone and other minor lithologies crop out extensively in the western Orocopia Mountains, including the Mecca Hills (Dibblee, 1954; Hays, 1957; Ware, 1958; Sylvester and Smith, this volume). Most of these strata were laid down at the deforming margin of the Salton Trough as alluvial fans extending southwestward into playas. They are severely deformed along faults of the San Andreas system, and adjacent to the Hidden Springs fault zone and at places the beds are folded isoclinally with steeply plunging hingelines. These beds and their attendant structures are best observed in the Painted Canyon region (Sylvester and Smith, this volume), along Box Canyon (Highway 195), and in the Hidden Springs-Grotto region. On the geologic sketch map (Fig. 1), these formations are grouped together and shown with the symbol PQ (Pliocene and Quaternary).

Unconformably overlying the Palm Spring Formation are fanglomerates assigned to the Ocotillo Conglomerate (Fig. 1, Qt_1) (Dibblee, 1954, p. 25; Sylvester and Smith, this volume). Along the San Andreas and Hidden Springs fault zones the Ocotillo Conglomerate is deformed and at a few places it dips nearly vertically. Southwest of the San Andreas fault, and northwest of Painted Canyon, the conglomerate consists of debris of Orocopia Schist, with current imbrication and facies relations showing derivation from the northeast from a direction now covered by deposits of the older Palm Spring Formation. Right-slip of the order of 20 km (12 mi) is needed on the fault to offset these exposures of the Ocotillo Conglomerate from their source area in the Orocopia Mountains (Ware, 1958).

The youngest sedimentary units in the region, of late Pleistocene and Recent age, include fanglomerates, terrace deposits, and alluvium. Bordering the Salton Sea are widespread deposits laid down by Lake Cahuilla, some of which are replete with small gastropods and other shells. This lake occupied the Salton Trough in quite recent times as shown by the remains of Indian camps around its shoreline. Bars, spits, and other shoreline features are today still fresh and easily recognized near the present sea-level contour.

VOLCANIC ROCKS

In addition to the basalts and andesites of the Diligencia Formation, several other volcanic rocks are exposed within the Orocopia region. These include felsite dikes which have tentative K-Ar dates of about 24 m.y. (Sylvester and Smith, this volume). The dikes of several types range in composition from pyroxene andesite to sanidine rhyolite and include a rapakivi-textured quartz latite porphyry in terrain south of Salton Creek Wash. Several rhyodacitic to rhyolitic domes crop out along the Salton Creek fault (Fig. 1, v_4). The quartz latite porphyry also occurs in the Painted Canyon area. Debris identical to this distinctive rock has been found in Soledad Basin (Ehlig and Ehlert, 1972). These and other volcanic rocks in the region are now under study by Crowe (1973; see also, Ehlig and others, this volume).

STRUCTURE

Deformational events recorded in the Orocopia Mountains includ those associated with the multip intrusion and metamorphism of th Precambrian and Mesozoic basemen rocks, those associated with the placement of the Orocopia thrust and include several intervals of complex folding and faulting dur the Cenozoic (Fig. 2).

Orocopia Thrust

Basement rocks lie in thrust tact upon Orocopia Schist along northeastern slope of the Orocop Mountains. Here gouge zones and fault slices accompanied by loca lenses of mylonite and blastomyl ite, suggest that major deep-sea thrusting was followed later by shallow reactivation. The thrus probably took place in late Cret ceous or early Paleocene time be cause granitic plutons of these sumed ages (based on regional re lations) are confined to the upp plate and are truncated below by thrust. Rare minor folds in the metamorphic rocks both above and below the thrust have not yet be studied sufficiently to determin the movement direction. Since thrusting, the Orocopia thrust h been broadly folded; the underly Orocopia Schist has apparently a justed to this folding by flexur slip along foliation surfaces. northwest-trending crest of the Orocopia Mountains, for example, antiformal through the region wh the Orocopia thrust has been bre ed by erosion. Rocks characteri of both the upper plate and the underlying schist crop out in di persed outcrops beneath Cenozoic sedimentary rocks throughout the Mecca Hills. It is therefore co cluded that in this region the

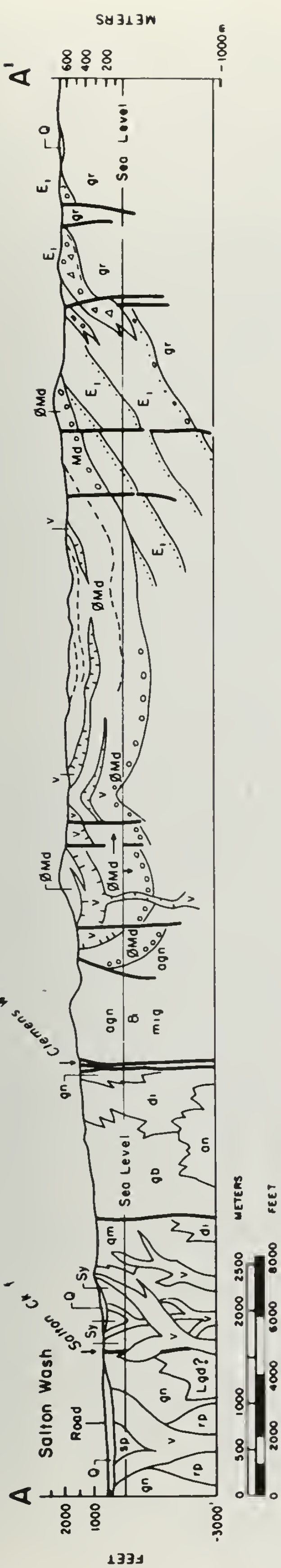

Figure 2. Simplified geologic cross section along line A-A' of Figure 1.

thrust lies beneath the gneisses and related rocks, and separates these from the underlying schist. Later faulting and folding during the Cenozoic have broken up and deformed the thrust plate; the plate was still later breached by erosion before deposition of the upper Cenozoic formations. The schist exposures represent places where the overriding plate was eroded away before these sediments were deposited.

Within the Orocopia region, the Orocopia thrust can be recognized in the sector between the San Andreas fault on the southwest and the Clemens Well fault on the northeast. The thrust has many similarities with the Vincent thrust in the San Gabriel Mountains (Ehlig, 1958, 1968), with the Chocolate Mountain thrust in southeasternmost California (Haxel and Dillon, 1973; Dillon and Haxel, 1975), and has some similarities with the Mule Mountain thrust about 130 km (80 mi) to the east (Pelka, 1973). A major tectonic problem in southern California is to work out the timings and correlations between these major movement zones (Crowell, 1974).

Faults of the San Andreas System

In addition to the San Andreas fault itself, which is well exposed near the mouth of Painted Canyon (Hays, 1957; Ware, 1958; Sylvester and Smith, this volume), several other major vertical fault zones, both active and inactive, trend northwesterly across the Orocopia region (Fig. 1). The Painted Canyon and Eagle Canyon faults are interpreted as abandoned splays of the San Andreas fault itself, and landforms along them due to active movements today have not been recognized. The Hidden Springs fault, on the other hand, cuts recent alluvium and is active, especially on the south where it trends towards the San Andreas fault. At the northwest, however, its course is obscure. Along with the nearby Clemens Well fault, it extends into an area of fault scarps cutting alluvium on the north flank of the Mecca Hills near Interstate 10.

The Clemens Well fault is a major strike-slip fault, and canyons incised across it show several meters of gouge and crushed rock with near vertical shears and phacoids. Fault slices of volcanic rocks from the Diligencia Formation now occur well to the northwest of their source region on the southeast. These slices within the fault zone indicate right slip on the Clemens Well fault but the magnitude of the total slip is unknown. It is unlikely that the slip is greater than several tens of kilometers at the most. Debris from southwest of the fault eroded from the upper plate of the Orocopia thrust is found in the conglomerates and sedimentary breccias of the Diligencia Formation, now northeast of the fault, and are but little offset. The extent of the Clemens Well fault to the southeast is unknown; on the northwest it is also unclear how it meets the Hidden Springs fault and how both or either of these in turn extend on farther to the northwest.

Other Faults and Folds

At the southeast, rock units and structures are truncated by the Salton Creek fault, which has a roughly east-west trend and has also provided channels for silicic volcanic rocks that now crop out as small disected domes along the fault trace. Although displacement of the Salton Creek fault is unknown, be- ment rocks to the south, includi Lowe (?) Granodiorite, are quite different from those to the nort (Fig. 2).

North of the Clemens Well fau in the eastern Orocopia Mountain terrain underlain by the Diligen and Maniobra formations is both folded and faulted. Most of the faults in this region are nearly vertical, and have either a nort easterly trend or a northwesterl trend. Several of the northeast striking faults in the Canyon Sp region offset fold axes left lat ally; in fact, on at least two o these, the fold hinge-lines show left slip that is nearly horizon in orientation and up to a kilom in magnitude.

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STRUCTURE SECTION ACROSS THE SAN ANDREAS FAULT ZONE, MECCA HILLS

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RACT

ne Mecca Hills lie on the northeast
in of the Salton Trough and consist of
Cenozoic crystalline basement rocks
lain by late Cenozoic nonmarine sedi-
ary rocks. Two parallel, northwest-
ding fault segments of the San Andreas
system subdivide the area into three
cturally distinct domains: a relative-
ndeformed marginal platform on the
heast; a folded and faulted zone 1.5
ide between the two faults; and an
rred basin block to the southwest.
faults are high-angle, nearly planar
ctures that locally flatten abruptly
rd into low-angle thrusts which carry
es of sedimentary rocks short distances
the platform and basin blocks.
ciated folds trend west-northwest,
que to the faults and in a step-right
chelon arrangement. Where exposed in
central block, the basement-sediment
rface is also folded. Basement in the
clinal cores is pervasively fractured
appears to have adjusted cataclasti-
to contractional strain, whereas the
mentary mantle folded passively in
onse to deformation at the basement
. The details of these structures
best observed in Painted Canyon which
s a relatively deep structural pro-
across the faults and the three struc-
domains.

DUCTION

ne Mecca Hills offer some of the best
sures and examples of the tectonic geo-
related to the southern San Andreas
zone, because structural and topo-
ic relief is relatively high, and
is little or no vegetation and
vial cover.

nis field guide focuses upon Painted
on in the center of the area where the
st and most representative structural
le can be conveniently studied. The guide begins in the upper reaches of the canyon where the structure is simple and proceeds down the canyon into the folded and faulted rocks of the fault zone. The guide is based upon previous studies by Dibblee (1954), Hays (1957), Ware (1958), and Sylvester and Smith (1975).

STRUCTURAL AND LITHOLOGIC OVERVIEW

Structure

Four nearly vertical, northwest-striking faults are exposed in Painted Canyon or adjacent canyons. From northeast to southwest, these are: the Platform fault, the Painted Canyon fault, the Skeleton Canyon fault, and the main, most recently active trace of the San Andreas fault (Fig. 1). For the purposes of this report the Skeleton Canyon fault is considered to be a strand of the San Andreas fault. All but the Platform fault branch upward and flatten abruptly into low-angle thrust faults. The Painted Canyon and San Andreas faults subdivide the area into two tectonic domains or blocks that are distinguished mainly by the style and degree of deformation, but also by the type and thickness of the mantle of Cenozoic sedimentary rocks. As shown in Figure 1, the block northeast of the Painted Canyon fault is informally called the platform block; that between the San Andreas and Painted Canyon faults is the central block. A third domain, the basin block, is inferred beneath a thick cover of alluvium southwest of the San Andreas fault. The structural and lithologic contrasts among the three domains are summarized in Table 1.

BASEMENT

The basement is comprised of two main rock units: 1) the Chuckawalla Complex (Miller, 1944), which is chiefly Precambrian gneiss, migmatite, and anortho-

Table 1
LITHOLOGIC AND STRUCTURAL CONTRASTS AMONG THE THREE STRUCTURAL BLOCKS OF THE MECCA HILLS

Basin Block	Central Block	Platform Block
	Pre-Cenozoic Basement Rocks	
Not exposed	Highly sheared gneiss and granite of the Chuckawalla Complex	Moderately sheared to unsheared gneissic and plutonic rocks Chuckawalla Complex; Orocopia Schist
	Basement-sediment surface steeply tilted to the southwest	Basement-sediment surface gently inclined to southwest
	Cenozoic Sedimentary Rocks	
Alluvium	Arkose and conglomeratic arkose	Conglomeratic arkose and conglomerate
Thickness: 3000-5000 m (12,000-15,000 feet)	Thicker stratigraphic sequence than in eastern block (approximately 1750 m (5000 feet)	Relatively thin stratigraphic sequence (<750 m; <2000 feet
Structure of sediments beneath alluvial cover is not known	Broad open folds, locally appressed, and overturned, with axes oblique to traces of major faults	Virtually unfolded except for minor drag folds with axes slightly oblique to fault trends
	Steep west-trending normal cross faults	Steep-to-gently inclined northwest-trending normal faults

Table 2
THICKNESSES, AGES, AND LITHOLOGY OF CENOZOIC FORMATIONS IN THE MECCA HILLS (after Dibblee, 1954)

Formation	Lithology
Canebrake-Ocotillo Conglomerate (Pleistocene) 0-750 m (0-5000 feet)	Gray conglomerate of granitic debris in central Mecca Hills, reddish conglomerate of schist in eastern Mecca Hills.
Palm Spring Formation (Pliocene (?) and Pleistocene) 0-1200 m (0-4800 feet)	Upper member: thin-bedded buff arkosic sandstone grading basinward into light greenish sandy siltstone. Lower member: thick-bedded buff arkosic conglomerate and arkose with thin interbeds of grey green siltstone.
Mecca Formation (Pliocene) 0-225 m (0-800 feet)	Reddish arkose, conglomerate, claystone; chiefly metamorphic debris in basal strata.

site and related rocks intruded by Mesozoic (?) plutonic granitic rocks, and 2) the Orocopia Schist which is thought to have been regionally metamorphosed during late Mesozoic time (Ehlig, 1968). The Chuckawalla Complex is thrust up rocopia Schist in the Orocopia Moun- (Crowell, 1962; and this volume), but e Mecca Hills, the two rock units are ated by the high-angle Platform fault 1) and Eagle Canyon fault (Hays, whose displacements are not well-ented.

OIC STRATIGRAPHY

te-Tertiary and Quaternary nonmarine entary rocks (Table 2), including calated alluvial fan, braided stream, acustrine deposits, rest unconform-upon the basement. Stratigraphic nesses, age relationships and correla-of various rock units across faults ot well-known in the area because of ous depositional discontinuities, t lateral and vertical facies changes, ack of fossils and distinctive marker The gross nature of the stratified nce, however, records a period of nental deposition near a tectonically e basin margin. Clast lithology and entary structures show that the sedi-ry detritus was derived from the nwood, Little San Bernardino, and pia Mountains to the northeast and as it is today.

e Mecca Formation (Table 2) is the t unit of the Cenozoic sequence. Com-chiefly of dark-red-weathering tus locally derived from the Chucka-Complex and Orocopia Schist, it forms conformable blanket from 2 to 5 m upon the basement northeast of the ed Canyon fault. It is much thicker oarser southwest of the same fault the contact with the basement is a ess unconformity.

e Palm Spring Formation (Table 2) rs to mark an abrupt change in pro-ce in that it was derived almost ely from a granitic terrane. Its ition in the Mecca Hills area marks preading of alluvial fans from the nwood and Little San Bernardino ains across the Mecca pediment to the Like the Mecca Formation, the Palm g Formation thickens abruptly across ainted Canyon fault and is progressively finer-grained basinward. Numerous diastems within the formation southwest of Painted Canyon fault indicate depositional interruptions reflecting Plio-Pleistocene episodes of folding and faulting at the margin of Salton Trough.

STRUCTURAL PROFILE

Upper Painted Canyon:
Platform Block. The upper part of Painted Canyon is incised into the northeastern tectonic domain: the platform block. Near the dry waterfall (Fig. 1) is the best place to observe the relatively undeformed character of the basement and overlying sedimentary rocks, the details of the nonconformable contact, and the geometry of subsidiary faults and associated minor drag folds.

The dry waterfall prevents further access up the canyon by motor vehicle. It is cut into migmatite of the Chuckawalla Complex that is massive and unfractured in contrast to that in the central block. About 200 m up the canyon from the dry waterfall are exposures of anorthosite and related rocks that Crowell and Walker (1962) described and correlated with similar rocks on the west side of the San Andreas fault in the Transverse Ranges. Farther up the canyon, these and other rocks of the Chuckawalla Complex are juxtaposed against the Orocopia Schist by the high-angle Platform fault (Fig. 1). Nearly horizontal slickensides show that the latest movement was horizontal, but drag folds with nearly horizontal axes indicate that a significant component of vertical separation has occurred as well.

The basement is overlain nonconformably by beds of the Mecca and Palm Spring Formations that are much thinner and typically composed of coarser and more angular detritus in this block than in the central block. The contact is a nearly planar, pre-Mecca Formation erosion surface into which channels up to 5 m deep were incised and filled with very coarse and angular Mecca Formation detritus. The erosion surface and overlying strata dip gently southwestward when mapped from canyon to canyon; except for faulting and minor drag folds adjacent to the faults, however, the Cenozoic sequence is undeformed in the platform block.

Central Painted Canyon:
<u>Central Block</u>. The central block is a 1.5 km wide, northwest-trending zone of broad open folds and relatively minor high-angle faults bounded by the Painted Canyon and San Andreas faults (Fig. 1). North of Painted Canyon the axial traces of most folds trend about N70°W and define a step-right *en echelon* pattern in the central part of the block; near the edges of the block, however, the folds are appressed, overturned in some instances and trend parallel to, or are truncated by the Painted Canyon and San Andreas faults. The largest and most prominent of these folds is the Mecca Anticline that comprises the topographically highest terrane northwest of Painted Canyon. Only part of the crest and the southwest limb of this fold project into the area shown in Figure 1, whereas the slivers of basement exposed along the Painted Canyon fault represent the core and structurally deepest exposures of the anticline.

Painted Canyon probably received its name from the varicolored exposures of basement and overlying Mecca Formation in the central part of the canyon around localities B, J, and C (Fig. 1). Here dark migmatitic gneiss, intricately intruded by small, irregularly-shaped bodies of white Mesozoic (?) granite and light orange and yellow felsite dikes (K-Ar age about 24 m.y.), is overlain by a very coarse, bouldery facies of dark red-brown-weathering Mecca Formation. The contact is a low-angle buttress unconformity that is best observed on the west wall of the canyon at locality B where it is tilted 60° to the southwest. The contact and overlying beds are folded into a northwest-plunging anticline at locality D. There the northeast limb of the anticline is truncated by the Painted Canyon fault; elsewhere, however, structurally higher parts of the northeast limb are overturned and thrust short distances upon the platform block (lo ity C, Fig. 1). In contrast to the r tively unsheared basement in the plat block, the basement in the anticline locality D and adjacent to the Painte Canyon fault, such as at J, is pervas ly fractured and sheared into a granu ed mass of rock fragments ranging typ cally from 0.5 to 5 cm in diameter. degree of fracturing is highest next the fault. The overlying sedimentary rocks, however, are strongly sheared within a meter or so of the fault pla the basement-sediment contact is not plane of slip. These field observati are interpreted as showing that in re ponse to contractional strain, the ba ment adjusted cataclastically by slip old fractures and shear planes that a assumed to have formed during a long history of pre-Mecca Formation deform tion in the San Andreas fault zone; t sedimentary cover responded to deform tion at the basement level by folding passively, partly by intergranular sl and partly by flexural slip concentra on thin claystone and mudstone beds. mechanism might be analogous to passi warping of a pliable material over a strained and deformed mass of bucksho

A small anticline and syncline are prominently exposed in the northwest of Painted Canyon at locality E (Fig. They are relatively minor structures are not shown on the map, because the die out vertically and laterally in v short distances; they do not project across the canyon to the southeast wa and are only gentle flexures in the n canyon to the northwest. These folds others similar in style and position the northeast edge of the central blo are interpreted as having formed in r ponse to shortening of beds in the fo limb shared by the basement-cored ant cline, described above, and the Skele Canyon syncline (Fig. 1).

<u>Painted Canyon Fault</u>. The Painted Ca fault is a major structural disconti at least 24 km long and is defined b zone of crushed rock and fault gouge a few centimeters to several meters w

fault surface dips more steeply in on bottoms than on adjacent ridges, ing that it is concave downward in s-section. Beneath the low-angle seg- s, footwall strata of the platform k are dragged abruptly to vertical and turned attitudes. The magnitude and e of slip are not known except for the Mecca Formation vertical component n locally exceeds 150 m as determined offset of the basement-Mecca Formation nformity.

he geometry of Painted Canyon fault and associated structures is displayed best he walls of central Painted Canyon as n diagrammatically in Figure 2. The cture is essentially that of an over- ed, faulted anticline in the hanging and an overturned syncline in the foot- . A sequence of beds in the overturned line is buckled between older and ger strata in the way that the pages of at-lying book might be shoved and fold- etween their covers. The buckled beds bounded by a triangular arrangement of - and low-angle faults that are best rved in Little Painted Canyon at local- F. The thrust faults and associated s are additional manifestations of con- tion and uplift of parts of the central k with respect to the platform and n blocks.

r Painted Canyon:
lower part of Painted Canyon, while l within the central block, is a ctural depression in contrast to the ctural culmination where the basement xposed against the Painted Canyon fault. he proceeds down the canyon, he rises ection stratigraphically from the a Formation, through the lower and r members, respectively, of the Palm ng Formation (Table 2; Fig. 1).

he lower member of the Palm Spring ation dips steeply down-canyon as part he southern and locally overturned k of Mecca Anticline. Gently folded undulating strata in the upper member he Palm Spring Formation nearer the n of the canyon connect with more tly appressed folds northwest and southeast of the canyon.

San Andreas-Skeleton Canyon Fault Zone:
The southwest side of the central block is bounded by a complex zone of faults and folded sedimentary rocks. At the mouth of Painted Canyon the relatively low structural and topographic relief precludes good exposures of these structures, but they may be studied in Skeleton Canyon, a major tributary marked by low hills of brick-red phacoid-bearing fault gouge of the San Andreas fault on the southeast side of Painted Canyon (locality G). The faults are convex-upward in cross-section and steepen with depth. Locally, tight and nearly vertical folds occur beneath low-angle segments of the gouge zones, such as at Locality H. There arkosic sandstones and interbedded siltstones of the upper Palm Spring Formation are strongly folded into steeply-plunging open folds in the core of an overturned syncline beneath a northeast-dipping thrust segment of the San Andreas fault.

The most recently-active trace of the San Andreas fault is marked northwest of Painted Canyon by aligned gulches and ridge notches, offset stream courses, fault gouge, nearly vertical shear surfaces with horizontal slickensides, and en echelon fractures and fault scarps in alluvium. Interpretations of several of these features are complementary and consistent, and indicate right-slip movement with local vertical uplift.

Basin Block:
Geophysical studies by Biehler (1964) and Biehler, Kovach and Allen (1964) indicate that the depth to basement ranges from 2000 m to as much as 5000 m beneath Coachella Valley. A steep gravity gradient across the San Andreas fault in the Mecca Hills area probably indicates a near vertical step of the basement-sediment interface of at least 4000 m. Thus, the San Andreas fault is the principal structural boundary between the Salton Trough and the high standing terrane to the northeast in the Mecca Hills.

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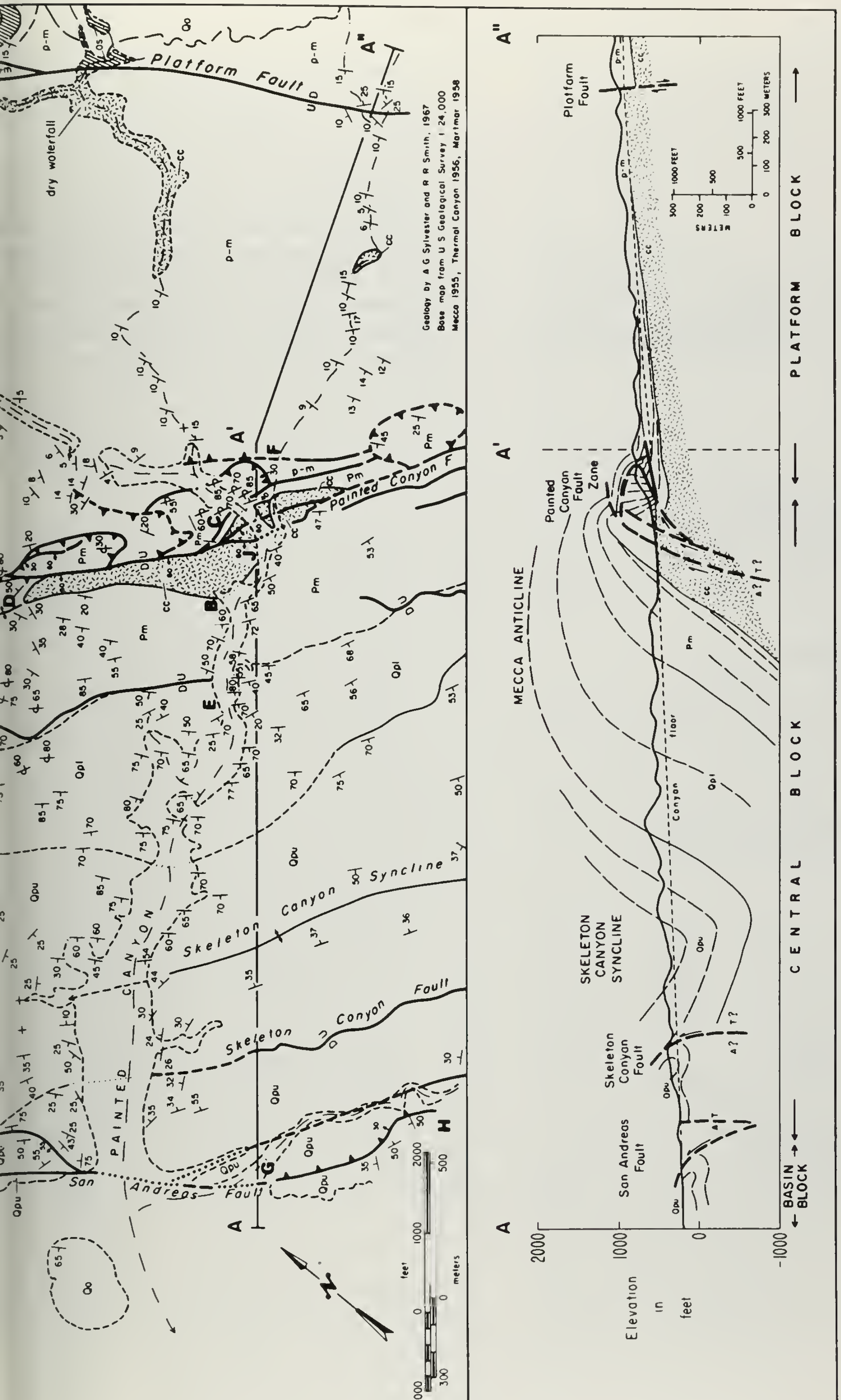

Figure 1.
Geologic map and structural profile of Painted Canyon, Mecca Hills. Symbols (oldest to youngest): Chuckawalla Complex (cc); Orocopia Schist (os); Mecca Formation (Pm); Palm Spring Formation (Qpl, lower member;Qpu,upper member); Palm Spring and Mecca Formations, undifferentiated (p-m); Canebrake-Ocotillo Conglomerate, undifferentiated (Qo).

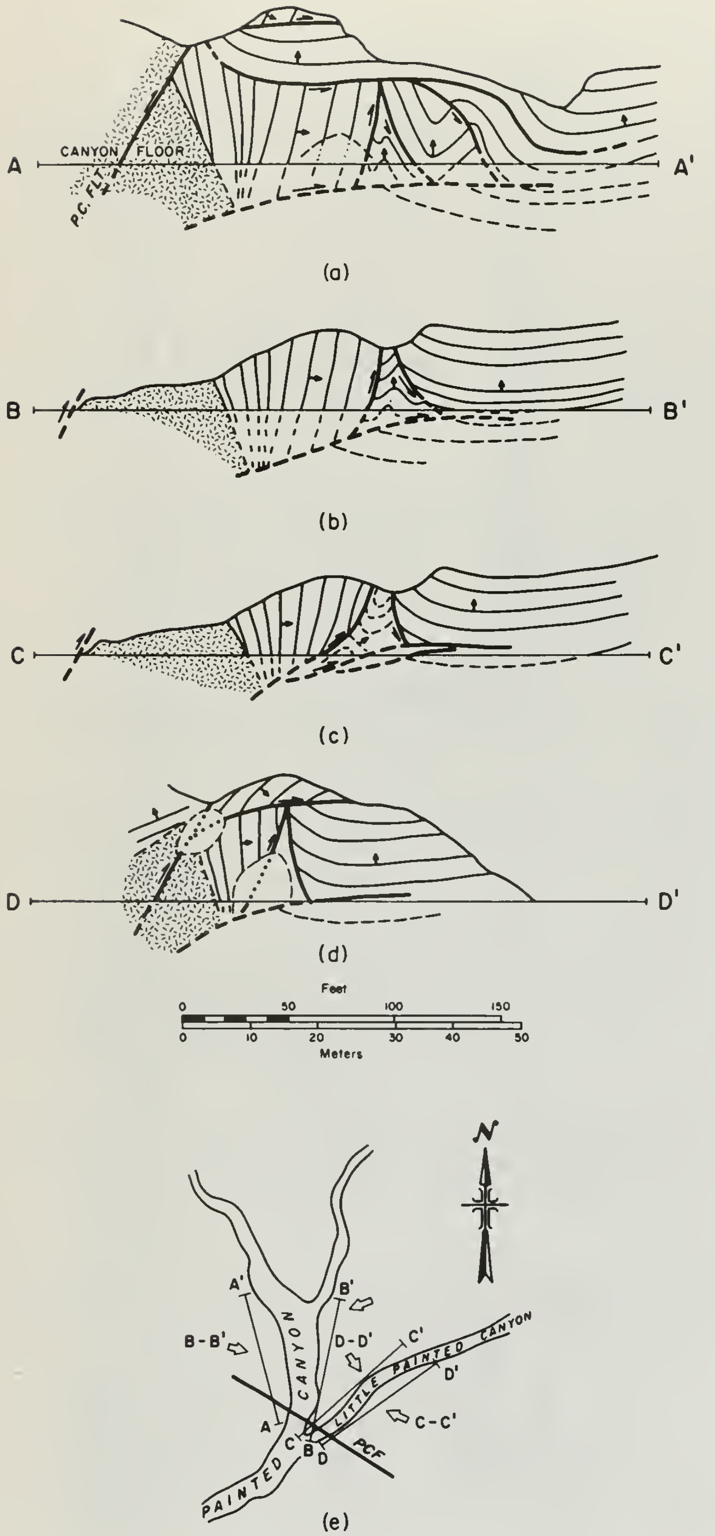

Figure 2.

Generalized cross-sections of buckled beds and low- to high-angle faults in the footwall of the Painted Canyon fault. (a) Northwest wall, Painted Canyon; (b) Southeast wall, Painted Canyon; (c) Northwest wall, Little Painted Canyon; (d) Southeast wall, Little Painted Canyon; (e) index map showing locations of cross-sections. In (a), (b), (c), and (d) arrows indicate tops of beds. In (e) open arrows indicate view points for cross-sections.

GEOLOGY OF THE COACHELLA FANGLOMERATE

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ACT

e Coachella Fanglomerate is located en the north and south branches of an Andreas fault in the vicinity of water River, north of Palm Springs. anglomerate consists of up to 1500 m arse conglomerate and breccia with bedded minor sandstone lenses and vided into two units: a light gray unit that is predominately fluvial lower, dark-colored unit that is y composed of debris-flow deposits.

e fanglomerate formed as a large ial fan or bajada in a deep sub- g basin 10.0 ± 1.2 m.y. ago (Mio- , and was derived from a source north of the Mission Creek fault. ource area was composed of meta- ic, granitic and volcanic rocks. nic clasts in the fanglomerate ase in abundance up-section at the se of granitic clasts while the ntage of metamorphic clasts remains ant, thus indicating that the char- of the source area was changing gh time. Roundness of melanocratic tic clasts increases up-section mean size decreases. This indi- that the source area was being d northward through time.

stinctive clasts of porphyritic z monzonite and magnetite occur n the fanglomerate and appear to been derived from a source area near argo Muchacho Mountains. Such a cor- ion requires 215 km of right-separ- within the San Andreas fault system.

DUCTION

e Coachella Fanglomerate consists of 0 m thick, east-dipping, well indur- Miocene fanglomerate. The fanglom- is exposed over an area of approx- ly 17 km^2 near Whitewater, California at the east end of San Gorgonio Pass. The fanglomerate has been previously mapped and described by Vaughn (1922), Allen (1954, 1957), Dibblee (1954) and Proctor (1968). In the present study, the fanglomerate is described in greater detail and its environment of deposition interpreted. Because the Coachella Fanglomerate lies immediately south of the Mission Creek fault (north branch of the San Andreas fault) and sediment-transport directions indicate a source area north of the fault, information may be obtained concerning strike-separation along this portion of the fault since the time of deposition of the fanglomerate.

SUMMARY OF REGIONAL GEOLOGY

Basement Rocks

Basement rocks in the region were first mapped by Vaughn (1922) and later by Allen (1957) who named the basement terrain north of San Gorgonio Pass the San Gorgonio igneous-metamorphic complex. The most widespread rock type is migmatitic gneiss although slightly sheared augen gneiss, piedmontite-bearing gneiss and greenschist are locally present. The Cactus Quartz Monzonite, consisting of granitic rocks ranging from quartz monzonite to quartz diorite with subordinate granite, is present north of San Gorgonio Mountain.

Present beneath the Coachella Fanglomerate near Red Dome in Whitewater Canyon, and exposed along the south side of Mission Creek, is a slightly metamorphosed potassium-feldspar porphyritic quartz monzonite with large orthoclase phenocrysts. Clasts of identical mineralogy and texture are common throughout the Coachella Fanglomerate and are quite distinct.

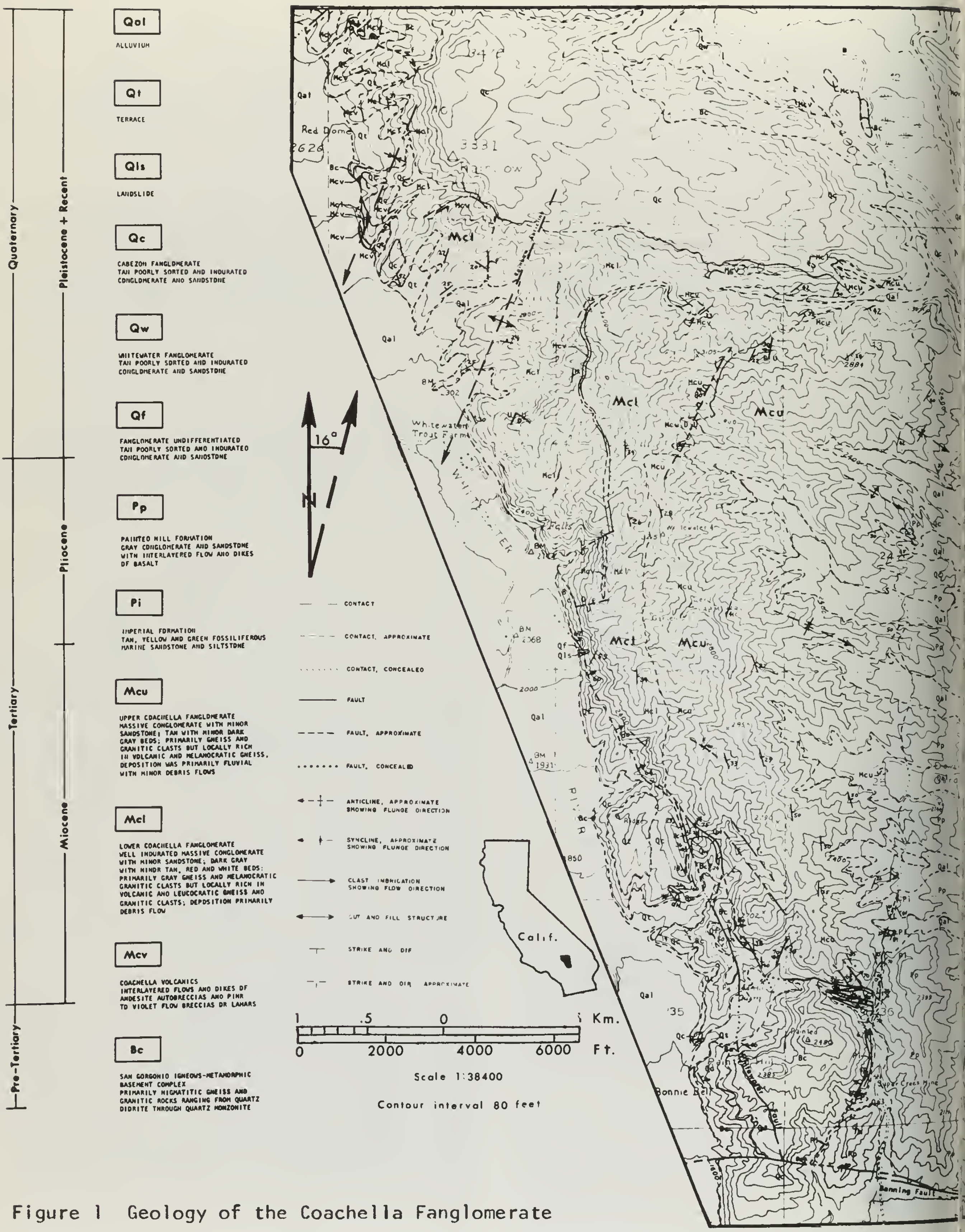

Figure 1 Geology of the Coachella Fanglomerate

tigraphy of Sedimentary Rocks

ne oldest sedimentary rocks in the on are those of the late Miocene Coa-la Fanglomerate (Fig. 2). These rocks probably correlative, at least in age provanance, with the Split Mountain ation of the Coachella and Imperial eys (Proctor, 1966).

ne lower Pliocene (Wilson, 1948; Dur-1950) Imperial Formation unconform-overlies the Coachella Fanglomerate. Imperial Formation ranges in thick-from 0 to 30 m in the study area and nes out to the north (Fig. 1). The ation consists of gray-green clay-e, siltstone and sandstone, locally in marine fossils.

ne Imperial Formation grades upward the Painted Hill Formation. These s consist of up to 1020 m of pale , coarse-grained conglomerate and sic sandstone (Allen, 1954). The ted Hill Formation may be correlative the Canbrake Conglomerate (Dibblee,) and the Palm Spring Formation dring, 1932; Dibblee, 1954; Proctor,).

ne Painted Hill Formation is uncon-ably overlain by the Deformed Gravels ne Whitewater River and the Cabezon lomerate, both Quaternary in age en, 1954, 1957). These formations st of poorly sorted, poorly bedded, ly and bouldery, tan arkosic sand-e with clasts of gneiss and granitic s and minor amounts of basalt (?) ghn, 1922). Proctor (1968) proposes the Cabezon/Whitewater Fanglomerates correlative with the Ocotillo Forma-of the Indio Hills.

HELLA FANGLOMERATE

ription

ne Coachella Fanglomerate was named by nn (1922) and was restricted and se-ted by Allen (1954, 1957). The type ion on the east side of Whitewater on at the trout farm consists of up to 1500 m of coarse-grained, well-indurated fanglomerate and may be separated into an upper and lower unit based upon color and mode of deposition (Fig. 2).

The lower unit is primarily dark gray, although low in the section concentrations of volcanic or leucocratic granitic and metamorphic debris give the rocks a red or white color respectively. The white units lense out to the east and south, indicating a north-westerly source, whereas the red units become indistinct in all directions.

The lower Coachella Fanglomerate is dominated by breccia deposits possessing only a crude stratification. Individual depositional units are generally unsorted and massive. Most clasts are matrix supported and lack any consistent orientation. The matrix of these deposits consists of approximately 40% silt, 35% sand and 25% gravel (Peterson, 1973) and are interpreted as being debris-flow deposits.

Well stratified deposits are also common especially near the base of the section. These deposits often show well developed clast imbrication. The matrix consists of approximately 20% silt, 70% sand and 10% gravel (Peterson, 1973) and are interpreted as being fluvial in origin.

The dark gray color of the lower unit is due to an abundance of melanocratic granitic and metamorphic clasts. Melanocratic granitic clasts are generally the most abundant, followed by volcanic, leucocratic granitic, metamorphic and potassium-feldspar porphyritic quartz monzonite, in that order. Clasts of magnetite also occur in small amounts but only in the northern part of the fanglomerate.

Approximately 250 m above the base of the section is a 23 m thick series of pale red and violet volcanic flows. The flows consist of olivine basalt and pyroxene andesite autobreccias or lahars (?). The volcanic rocks wedge out to the south and end abruptly on the north near a dike of similar material. The dike may represent the source of the flows. Professor Daniel Krummenacher at San Diego State University obtained a K-Ar date of 10.0 ± 1.2 m.y. on a sample of pyroxene andesite autobreccia.

The upper Coachella Fanglomerate is light gray to tan in color and is characterized by fluvial deposits. Debris-flows are present but to a much lesser extent than in the lower unit. Volcanic clasts are generally the most abundant, followed by melanocratic granitic, metamorphic and potassium-feldspar porphyritic quartz monzonite.

Lithology. In general, volcanic clasts tend to increase in abundance up-section in the fanglomerate at the expense of granitic clasts, whereas metamorphic clasts remain essentially constant. Clasts of potassium-feldspar porphyritic quartz monzonite show a marked decrease in abundance up-section.

Trends in clast lithology indicate metamorphic terrain as a source area wh granitic plutons decreasing in area of exposure with time. Volcanic sources parently increased in exposure with ti

The changes in clast lithology migh be due to juxtaposing the fan and diff ent source areas along a strike slip fault. Studies of sediment transport directions indicate that the source of the fanglomerate lies north of the pre ently active Mission Creek fault (nort branch of the San Andreas fault) (Fig. and using the present rate of movement of 2.6 cm/yr. and a rate of deposition c 0.33 m/100 yrs. (Bull, 1964a), approximately 11.7 km of right slip could have occurred during the time of depositior of the fanglomerate.

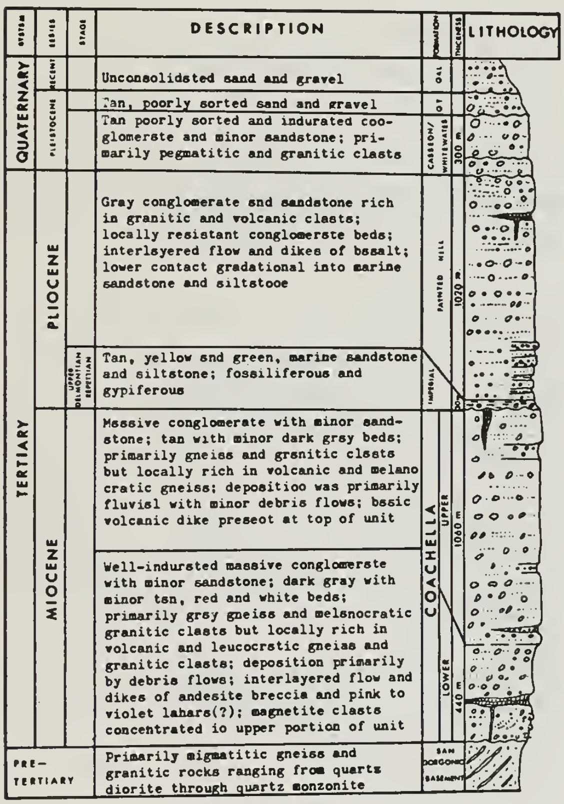

Figure 2. Regional stratigraphy.

Figure 3. Summary of 56 sediment transport directions.

he inverse relationship between volc and granitic clasts can also be ained by volcanic extrusions covering uch of the granitic source area. her possibility is that headward ero- within the source area progressed ugh a metamorphic and granitic terrain a volcanic terrain, thus changing the tive abundance of clast lithologies sited in the fan. This could have rred by erosion of drainage divides y drainage interception.

dness. Mean roundness of melanocratic itic clasts, within fluvial deposits compared to stratigraphic position and ral position within particular stratphic horizons. Roundness was found ncrease slightly up-section thus indi- ng an increasing distance of transport headward erosion of the source area ugh time. Paleocurrent data indicates rtherly source area (Fig. 3) and it expected that mean roundness would ease with distance from the northern- exposures of the fanglomerate, how- , results were inconsistent. This may xplained by debris-flows carrying lar clasts far out onto the fan and g reworked into fluvial deposits, thus easing the mean roundness.

. Sternberg's law (Pettijohn, 1957) icts an exponential decrease in size the distance of transport in rivers, Chawner (in Krumbein, 1942) and Barker 2) find the same relationship to be for alluvial fans. Mean maximum, intermediate diameters of melanocratic itic clasts, in fluvial deposits, in the Coachella Fanglomerate were ted on semi-log paper against the ance from the formations northernmost sures. Results show a general decre- in size with distance of transport, indicating a northerly source area.

mentology

ocurrent indicators. The primary s of ascertaining the paleo-slope and local direction of sediment transport by clast imbrication. Imbrication in the Coachella Fanglomerate is usually due to the impingement of one clast onto another although matrix-suppored imbricated clasts also occur. Cut-and-fill structurs are rather uncommon in the fanglomerate and no outcrops were found which gave a direction of sediment transport but six outcrops gave a line of movement, five of them have a northeast-southwest orientation. Only one occurrance of cross-bedding was found in the fanglomerate and it yields a direction of movement from the northeast to the southwest.

The composite plot of all paleocurrent indicators (Fig. 3) has a radial pattern which would be expected for alluvial-fan deposits, but it is also markedly bimodal. The average current direction is N02E with the direction of transport from the north to the south, but the bimodal distribution may indicate two separate source areas. Facies changes near the trout farm in Whitewater Canyon indicate that the present outcrop area of the Coachella Fanglomerate may have been a zone of confluence between two alluvial fans at the time of deposition. The paleocurrent data would tend to support this hypothesis.

Mode of deposition. The Coachella Fanglomerate is dominated by massive, poorly sorted depositional units of coarse conglomerate and breccia. Clasts up to 3 m are present and most are matrix supported. Some units are inversely graded but other sedimentary structures are rare. According to Fisher's (1971) criteria the writer interprets these units to be debris-flow deposits.

Many depositional units within the Coachella Fanglomerate are well stratified and often contain small sandstone lenses. Sedimentary structurs are common within these units and consist primarily of imbricated clasts. The writer believes these units are formed by fluvial processes.

Blackwelder (1928), Blissenbach (1954), Bull (1964a, b) and Hooke (1967) suggest that debris-flow processes are most dominant near fan apices, but such deposits are found throughout the

Coachella Fanglomerate, although they are concentrated in the lower portion of the section. This may indicate that the present exposure of the fanglomerate was deposited near the apex of a much larger alluvial fan and that the source area, and therefore the fan apex, was transgressing to the north with time.

Structure

Faults. The Whitewater fault (Allen, 1954, 1957) forms the western boundary of the Coachella Fanglomerate. It extends along the east side of the Whitewater River from its intersection with the Banning fault on the south, to at least Red Dome on the north (Fig. 1) (Riverside County Flood Control Office, 1971). Where exposed, the fault juxtaposes the Coachella Fanglomerate against rocks of the basement complex and Quaternary fanglomerate. The fault dips 60° to 80° to the east and displays both normal and reverse separations. The fault zone is usually marked by up to 2 m of basement gouge. Shear zones extend into the basement rocks for as much as 150 m but never more than a few meters into the Coachella Fanglomerate. Quarternary fanglomerates rarely show any evidence of deformation.

A series of small faults form the southern termination of the Coachella Fanglomerate and extend in a zone 200 m wide, from the Whitewater fault on the west to Super Creek on the east (Fig. 1). The faults are all nearly vertical and juxtapose rocks of the basement complex against the Coachella Fanglomerate in narrow fault slices. An olivine basalt dike (Allen, 1957), ranging in thickness from 2 to 20 m has been intruded along one of the faults. The faults were active between 8 and 10 m.y. ago, because they cut the upper Coachella Fanglomerate but are overlain by the Imperial Formation.

At its northern boundary, the Coachella Fanglomerate is overlapped by Quaternary fanglomerates and its full extent cannot be determined; however, the northwesternmost outcrop is in fault contact with the basement complex. The basement source area of the fanglomerate may have been uplifted along this fault.

Many small faults occur within the Coachella Fanglomerate and are general parallel to the major bounding faults, espicially the Whitewater fault. The largest of these lesser faults extends for approximately 1 km and shows norma dip separation of about 3 m.

Folds. The northwestern portion of th Coachella Fanglomerate is folded into broad open anticline and sincline tren ing N20E and plunging gently to the south-west (Fig. 1). The prominent volcanic flows interbedded within the lower uni were involved in the folding so that i western continuation is exposed in the core of the syncline. The volcanic fl in this area is actually two flows sep-ated by 5 m of dark gray fanglomerate.

Three very broad folds are present along the eastern margin of the Coachella Fanglomerate. Their fold axes trend NW and plunge gently to the southeast.

Location of Possible Source Terrains

Distinctive clasts of potassium-fel spar porphyritic quartz monzonite are sent throughout the Coachella Fanglome The potassium-feldspar occurs as pink phenocrysts up to 2 cm in diameter and set in a very dark matrix. Often the matrix possesses a greenish tinge due the presence of epidote. Microscopic examination reveals that the rocks hav been metamorphosed to lowest greenschi facies and large quartz grains have re crystallized into concentrations of sm ller quartz crystals. The rocks often contain xenoliths of quartz diorite co position. Basement rocks of this type outcrop beneath the fanglomerate in Wh water Canyon and south of the Mission Creek fault zone within Mission Creek Canyon, but none is known to be preser immediately north of the fault zone.

Magnetite clasts up to a meter in diameter, are present within the lower hella Fanglomerate. These rocks con- traces of muscovite and scapolite ell as veins of epidote. Their large and unusual mineralogy make them a distinct rock type. Similar rocks present as concentrations within the ssium-feldspar porphyritic quartz onite of Mission Creek Canyon, but is known north of the Mission Creek t zone.

t is possible that these rock types , at one time, present north of the ion Creek fault zone, and have since removed by erosion, implying little o lateral offset. It seems more ly that the source area has been dis- ed laterally, perhaps to the south- , but an unknown distance.

dentical clasts of potassium-feldspar hyritic quartz monzonite are present in Miocene (?) fanglomerates east of San Andreas fault near the southern of the Chocolate Mountains and with- he Bear Canyon Formation near the rado River. Also, basement outcrops ery similar quartz monzonite are ent on the west side of the Cargo acho Mountains. Magnetite bearing s are also present in the Cargo Mu- ho Mountains.

f the Southern Chocolate Mountains/ o Muchacho Mountains region were the ce area for the Coachella Fanglomer- it would require approximately 215 f right-separation since the time eposition. This corresponds to a rate of 2.15 cm/yr within the San eas fault system during the last m.y. These results are in keeping other studies using different rocks rated by the Southern San Andreas t (Crowell, 1962; Crowell & Walker, ; Ehlig & Ehlert, 1972).

LUSIONS

he Coachella Fanglomerate was depos- in an arid to semi-arid climate and derived from a complex area of meta- hic, granitic and volcanic rock types. source area stood at high relief and was eroded northward through time as suggested by increasing clast roundness and decreasing clast size up-section. Headward erosion of the source area is further supported by younger portions of the fanglomerate lying directly upon basement pediment in northern exposures. The abundance of debris-flow deposits and the presence of very large clasts (>3 m) throughout the fanglomerate indicate that the present outcrop of the formation was deposited near the apex of a very large fan or edge of a bajada. Volcanism occurred during deposition of the fanglomerate as indicated by the presence of a 23 m thick series of volcanic flows within the lower unit.

Studies based upon distinctive clast lithologies suggest that the source area for the Coachella Fanglomerate was along the western side of the Cargo Muchacho Mountains. The fanglomerate has subsequently been offset 215 km within the San Andreas fault system. Uplift of the source area may also have occurred within the same fault system.

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LATE QUATERNARY UPLIFT OF THE SAN BERNARDINO MOUNTAINS ON THE SAN ANDREAS AND RELATED FAULTS

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ACT

e San Bernardino Mountains were ted in late Quaternary time along orth of the San Andreas fault system he Pinto Mountain fault. This range mposed of two structural blocks of rent pre-Cenozoic basement rocks, posed along the San Andreas fault ts north branch (Mill Creek-Mission fault of Allen, 1957). The north is eroded from an elevated mass of ent that is part of the Mojave t crustal block, and the south block strip within the San Andreas fault m eroded from basement like that of an Gabriel Mountains. Uplift of the ernardino Mountains and thrusting their margins is attributed to ession that may be the effect of al obstruction of right slip on the ndreas fault system by left slip on into Mountain fault intersecting it the east.

DUCTION

is report summarizes the regional gy of the San Bernardino Mountains the author's own mapping (Dibblee, , b, 1967a, b, c, 1970, 1974a, b, npublished mapping listed by Rogers, , together with the author's pretations of its genesis and fault ents (Dibblee, 1967d, 1968b). The r's mapping and structural inter- tions differ from those of Vaughan) and Allen (1957).

e San Bernardino Mountains were ted within and north of the San as fault system west of its inter- on by the Pinto Mountain fault in rnary time to form the eastern sion of the Transverse Ranges. Up- of this range is apparently related ateral movements on these major s. In order to demonstrate this, it ecessary to indicate (1) the geologic ture of this range, (2) its geomorphic evolvement, (3) movements on the major faults that bound or transect it, and (4) its probable tectonic genesis.

GEOLOGIC STRUCTURE

The geology of the San Bernardino Mountains is generalized on figure 1, and its geomorphology as related to the major faults, on figure 2. As shown thereon, the San Andreas fault bifurcates south-eastward near San Bernardino into two strands, the north branch (Mission Creek fault of Vaughan, 1922, Allen, 1957, and Mill Creek fault of Allen, 1957) and the south branch. The San Andreas fault and its north branch divide this range into two structural blocks of different base-ment terranes, the north block and the south block (fig. 2).

The north block is eroded from an elevated mass of granitic basement that is part of the granitic batholith of the Mojave Desert and that contains pendants of gneiss and metasedimentary rocks. It is therefore geologically part of the Mojave crustal block and indeed was part of the Mojave Desert during Tertiary and probably early Quaternary time. The southwestern part of the north block from Cajon Pass to Barton Flats (fig. 1) is broken into several northward-tilted fault blocks that contain remnants of north-dipping Pliocene (?) fluviatile sediments (Crowder Formation, Dibblee, 1970, and Santa Ana Sandstone of Vaughan, 1922 in Dibblee, 1964b), indicating this part was a valley that probably extended southeastward from the Cajon basin in Pliocene(?) time. The bounding faults are vertical or steep.

The south block is within the San Andreas fault system. It is eroded from a gneiss--plutonic complex, mylonite, and (Pelona) schist, in that order of de-scending structural relations (fig. 1). This suite of rocks is like that of the San Gabriel Mountains to the west (Dibblee, 1968b, p. 266) and unlike that of the north block. These unlike blocks were therefore juxtaposed along the San

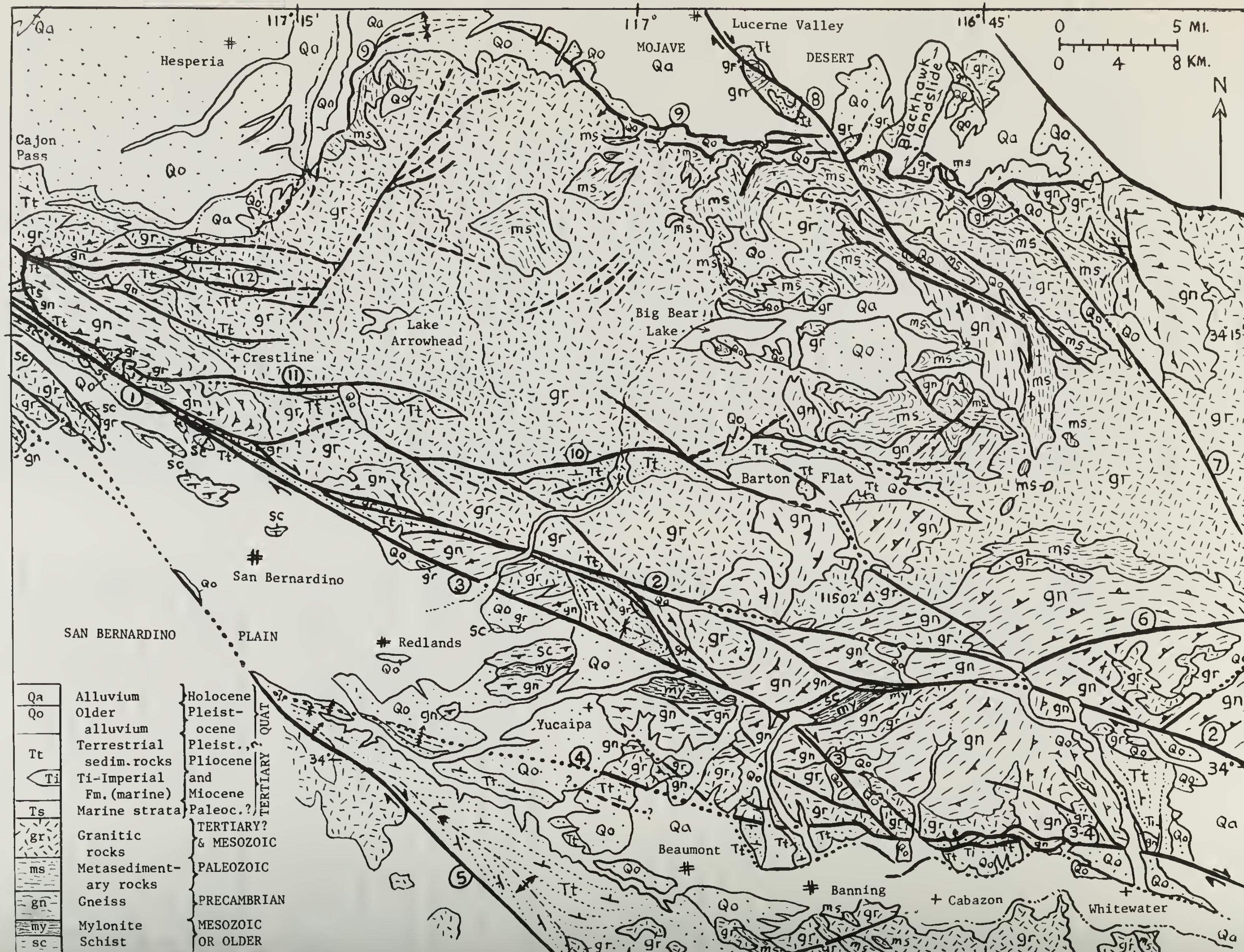

Figure 1. Geology of the San Bernardino Mountains. Generalized from Dibblee (1970). Major faults as follows: 1, San Andreas (active); 2, San Andreas north branch; 3, San Andreas, south branch (active); 4, Banning; 3-4, San Andreas south branch and Banning, combined; 5, San Jacinto; 6, Pinto

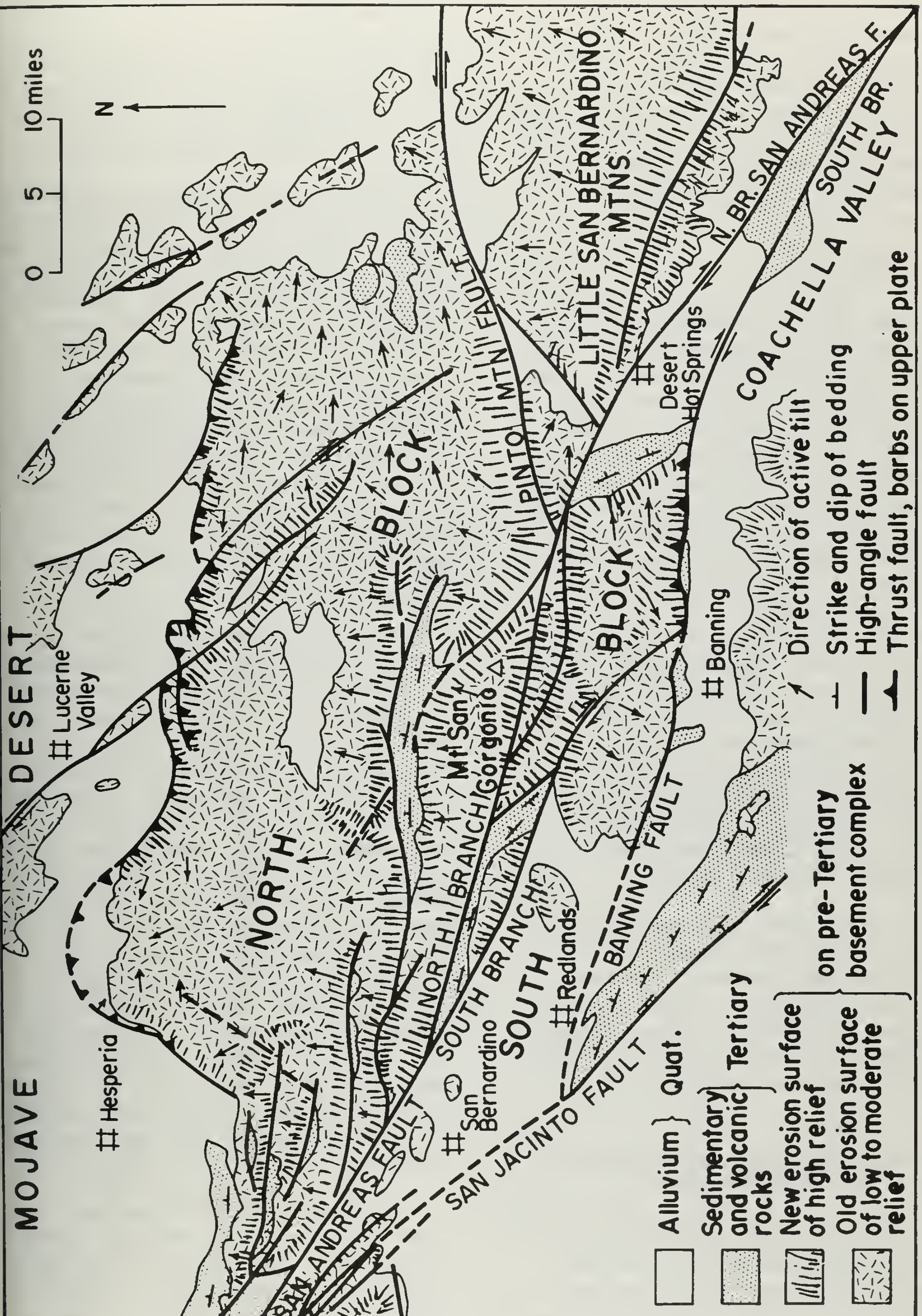

Figure 2.--Geomorphology of the San Bernardino Mountains and its relationship to major faulting.

Andreas fault and its north branch.

The south block is composed of two slices separated diagonally by the south branch of the San Andreas fault. The northeast slice is mountainous and contains Cenozoic sedimentary deposits (fig. 1). The southwest slice is of low relief and in large part covered by Quaternary alluvium and is not known to contain Tertiary strata.

GEOMORPHIC EVOLVEMENT

Because the San Bernardino Mountains are very young, the geomorphology of this range expresses the way in which it was elevated in late Quaternary time (fig. 2). When the north block was part of the Mojave Desert, its surface was eroded to low relief by early Quaternary time and was traversed by a small valley that now contains Big Bear Lake. In late Quaternary time the north block was elevated as shown (fig. 2) so that its old erosion surface is now a plateau. The fault-bounded margins of this block are steep, newly eroded fronts. Where there are no bounding faults, the old erosion surface is tilted outward toward the Mojave Desert. The southwestern part of the north block has been differentially elevated as several north-tilted fault blocks (fig. 2). As a result of its rapid uplift, this upland is being dissected by deep, youthful canyons.

The south block was only partly elevated in late Quaternary time. The northeast slice was elevated together with the north block and in part thrust southward east of Banning. The southwest slice remained depressed in its western part and in large part was covered by alluvium.

MOVEMENTS ON THE SAN ANDREAS AND RELATED FAULTS AND PINTO MOUNTAIN FAULT

The San Andreas fault system through the San Bernardino Mountains is a complex group of anastomosing high-angle faults within a strip bounded by the San Andreas fault and its north branch on the north and by the Banning fault on [the] south (fig. 1). Although movements o[n] this system were primarily right-slip during much of Cenozoic time, the San Bernardino Mountains apparently were elevated vertically on the north side [of] the San Andreas fault and its two branches in late Quaternary time.

In the San Bernardino Mountains th[e] north branch of the San Andreas fault forms a trenchlike gash through this range, especially south of its highes[t] part, striking N 75° W. Movement on [this] segment was upward on the north, as w[ell] as right lateral. However, this segme[nt] has not moved since sometime in the Pleistocene because part of it is cov[er]ed by dissected but unfaulted Pleisto[-]cene alluvium (Dibblee, 1964a). Rece[ntly] formed scarps that resulted largely f[rom] right-slip movements occur only at th[e] west end of this fault, and along its southeastward extension in Coachella Valley (fig. 2).

The San Andreas fault and its sout[h] branch southeastward to Banning strik[e] about N 60° W and bound the precipito[us] southwest front of the range, indicat[ing] vertical uplift on the northeast in l[ate] Quaternary time. However, fault scar[ps] and offset or deflected stream channe[ls] or canyons are prevalent along this alinement (Morton and Miller, this volume) and indicate right-lateral mo[ve]ments in Holocene time. Near Banning the south branch joins the east-trend[ing] Banning fault to become a north-dippi[ng] thrust fault for 11 km (7 mi) along which basement rocks are thrust over Cenozoic deposits, including Quaterna[ry] fan gravels (Allen, 1957; Dibblee, 19[..]) Eastward from Whitewater this combine[d] fault becomes vertical and resumes it[s] normal southeastward trend through th[e] Coachella Valley, (figs. 2, 4, 5).

The Banning fault near and west of Banning is nearly vertical where expo[sed] along which the basement complex on t[he] north is elevated against Cenozoic se[di]mentary deposits on the south; elsewh[ere] it is covered by dissected but unfau[lted]

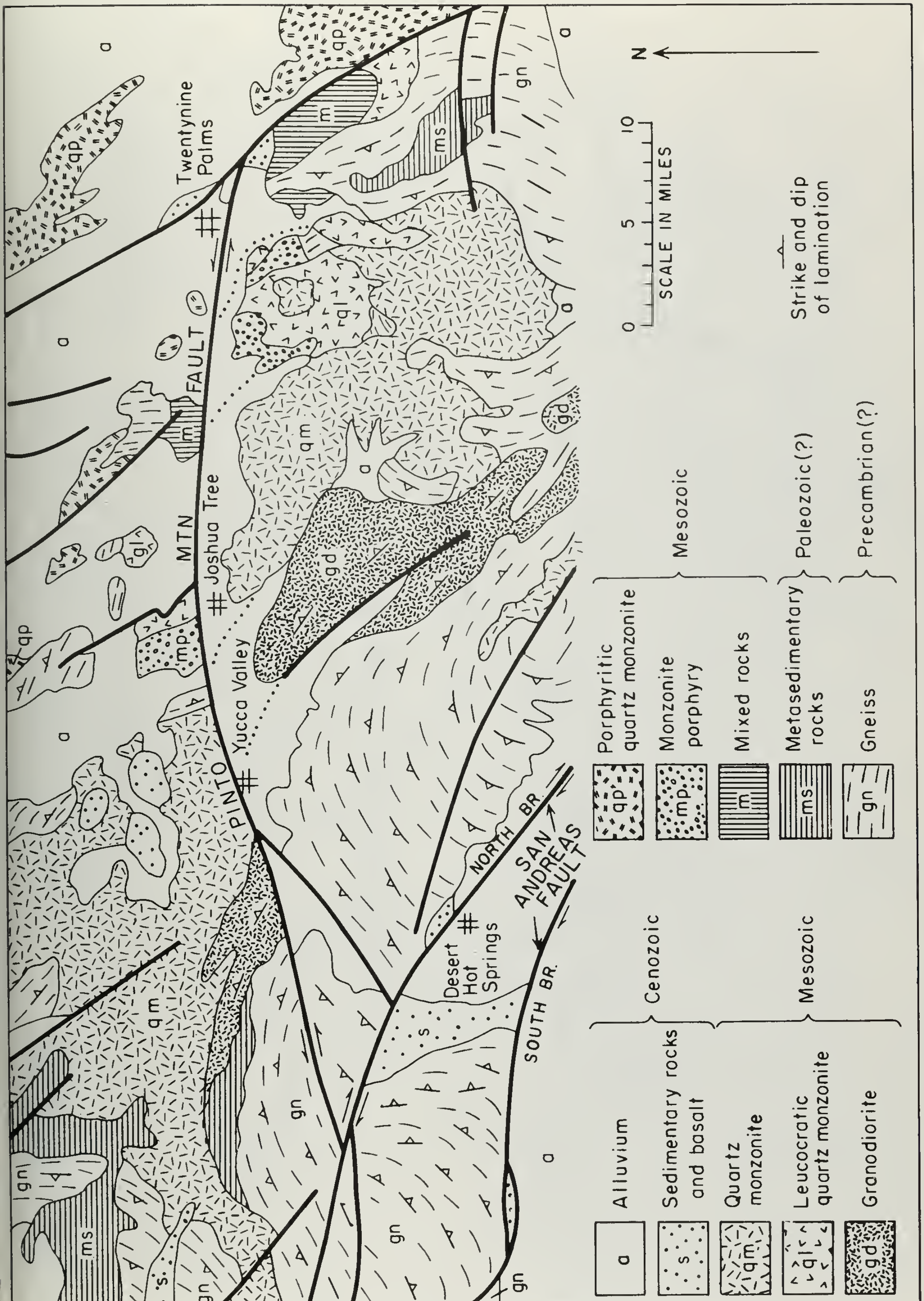

Figure 3.--Geology along the Pinto Mountain fault.

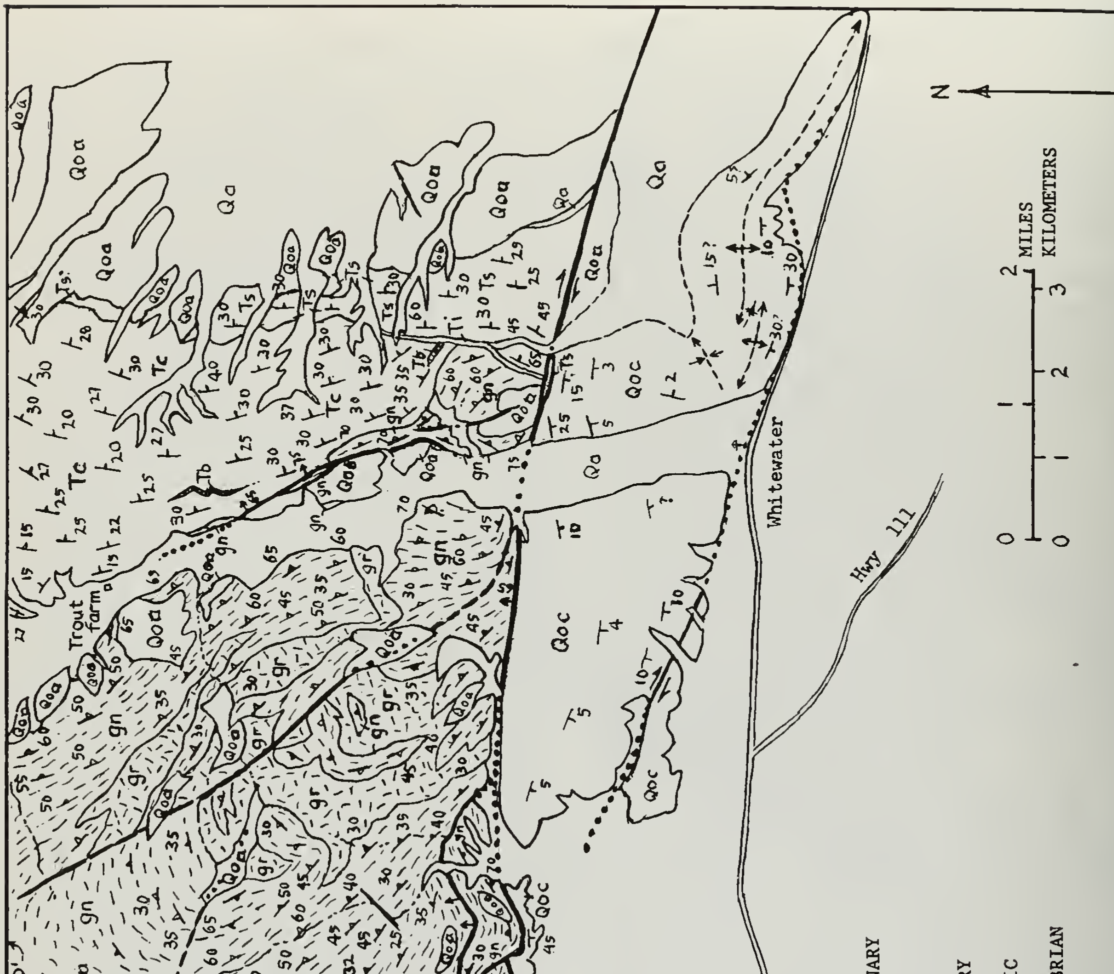

Figure 4. Geology along the combined Banning and south branch of San Andreas fault near Cabazon and Whitewater (Geology by T. W. Dibblee Jr., 1968).

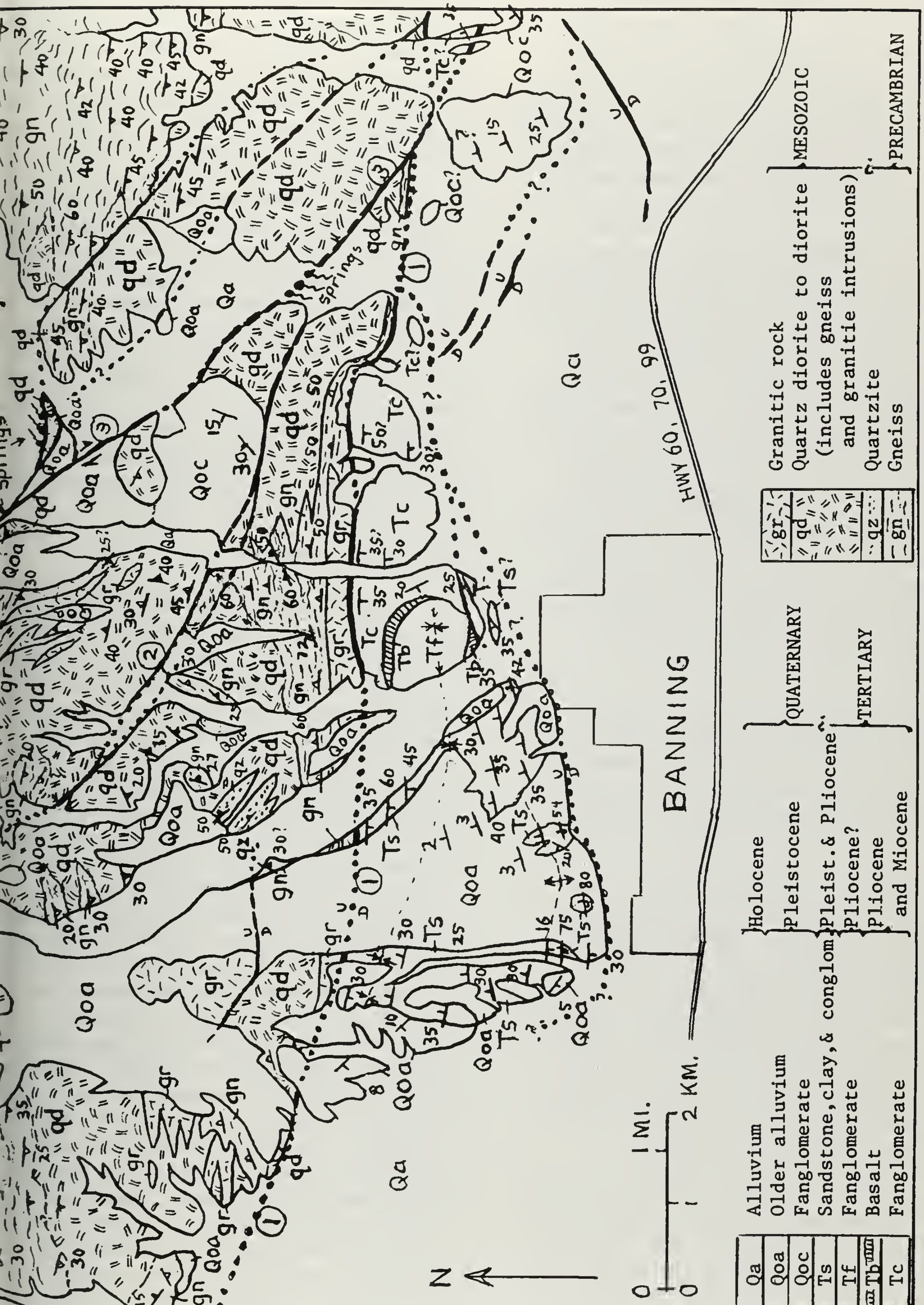

Figure 5. Geology along the Banning and south branch of San Andreas fault near Banning. Faults as follows: 1, Banning; 2, Gandy Ranch; 3, south branch of San Andreas (Geology by T. W. Dibblee Jr., 1968).

Pleistocene alluvium (fig. 1) and is therefore inactive. South of Redlands it presumably extends west under the Quaternary alluvium toward the younger San Jacinto fault along which it may have been displaced northwest about 18 km (13 mi) to what is now the Cucamonga fault along the south base of the San Gabriel Mountains (fig. 2).

The Pinto Mountain fault extends about 80 km (50 mi) eastward from its juncture with the San Andreas north branch fault into the Mojave Desert (figs. 2, 3), and is nearly vertical where exposed and locally forms scarplets in Pleistocene alluvium (Dibblee, 1967a, b, 1968a, 1970). Although displacement is up on the north at the western part of the fault, the main overall movement is left lateral ranging from nearly zero at its west end to a maximum of 16 km (11 mi) near and east of its mid-point (Dibblee, 1967d). This movement is indicated by displacement of pre-Cenozoic rock units and the displaced antiform structure in the gneiss (fig. 3).

The south-dipping thrust faults along the northern margin of the San Bernardino Mountains and associated right-lateral faults form north-facing scarplets across alluvial fan gravels (Dibblee, 1964a, 1967c, 1970, 1974a).

The earliest lateral movement on the San Andreas fault system in this area, presumably in Tertiary time, may have been along the Banning fault, along which the basement terrane of the south block of the San Bernardino Mountains was elevated and juxtaposed against that of the Peninsular Ranges to the southwest (Dibblee, 1968b, p. 271), but this movement ceased in Quaternary time as the fault became buried by alluvium.

A large amount of right-lateral movement on the San Andreas fault and its north branch prevailed in late Tertiary (?) and Quaternary time along which the gneiss, mylonite, and schist exposed south of this fault alinement may have been separated about 96 km (60 mi) from a similar suite of rocks exposed nort east of the San Andreas fault in the Orocopia Mountains (Dibblee, 1968b, 269, fig. 5). During that time this strand must have been the principal of transcurrent movement on the San Andreas fault system.

By late Quaternary time, right-sl apparently ceased on the north branch within the San Bernardino Mountains became transferred along the south b diagonally across the south block of this range to the old Banning fault, eastward from Banning, to reactivate that segment. The south branch in p may have formed as a new strand beca north of Banning it displaces south-dipping gneiss, mylonite, and schist the south block right laterally only 3 km (2 mi) or less (fig. 1).

TECTONIC GENESIS

Uplift of the San Bernardino Mountain resulted from compression that may b the indirect(?) effect of partial obstruction of right-slip on the San Andreas fault system by left-slip on intersecting Pinto Mountain fault or the stress that generated it. Left- movement on the Pinto Mountain fault indicates that the terrane north of moved westward relative to that sout it and has impinged against the San Andreas fault system to the west. Th transcurrent movement may have cause the segment of the north branch west this juncture to bend into a nearly trend, and may have similarly affect the western segment of the south bra and the Banning fault to the southwe if these segments originally transec this area with more uniform northwes trends. These nearly west-trending segments of the San Andreas fault sy including the west-trending segment the south branch that joins the Bann fault east of Banning, became barrie to the northwestward movement of the terrane southwest of this fault syst relative to that on the northeast, b cause these segments became oriented large angle to the direction of this iscurrent movement. But because this ement, if constant, is irresistible, terrane on one side of these nearly :-trending segments, the north side in ; area, has been compressed and forced ird to form the San Bernardino Moun- is. Outward thrusting at the margins this range, such as the southward isting on the south branch east of ning and the northward thrusting on northern margin, are effects of this pressive uplift, resulting in a north- th crustal shortening on and near this : of the San Andreas fault system.

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ACKNOWLEDGMENTS

Reviewed by Douglas M. Morton and Robert F. Yerkes

GEOLOGY OF THE SAN ANDREAS FAULT ZONE NORTH OF SAN BERNARDINO BETWEEN CAJON CANYON AND SANTA ANA WASH

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ABSTRACT

The San Andreas fault zone north of the City of San Bernardino ranges in width from a few hundred metres to 1.5 km and consists of branching and anastomosing faults. Physiographic expressions of recent surface fault displacement abound throughout the length of this segment. Midway in this segment the zone bifurcates southeastward into the north and south branches of the San Andreas.

Urban expansion of San Bernardino is extending northward into and across the San Andreas fault zone. This development should take into consideration the numerous faults within the zone as well as the potential for secondary effects of earthquakes such as landsliding, ground rupture, and ground lurching.

INTRODUCTION

The San Andreas fault zone is located in the path of urban expansion on the north side of the City of San Bernardino. This southern California area is the only part of the San Andreas fault zone south of the San Francisco Peninsula that is immediately in the path of current urbanization.

In the San Bernardino area the San Andreas fault zone consists of two major strands and bound the upper Santa Ana Valley and the south front of the San Bernardino Mountains. The juncture of these strands is an area of moderate relief, which is considered by many developers as desirable for building sites above the valley floor. This report summarizes the geology of a 38-km segment of the San Andreas fault zone north of San Bernardino between Cajon Canyon on the northwest and Santa Ana Wash on the southeast.

Unlike the San Andreas zone to the northwest, where numerous minor physi graphic fault features are observable and mappable (Barrows, this volume), heavy vegetation and landslides obscu most of the minor fault features.

GENERAL CHARACTERISTICS OF THE FAULT NE

This segment of the San Andreas fa t zone consists of multiple faults cons - tuting a zone generally 500 to 1,000 wide (Fig. 1b-g). In general, the southern part of the zone contains ge morphic evidence of the most recent s - face fault displacement. The trace o the most youthful breaks is marked by scarps, sag ponds, and right-lateral offset drainage courses. At several localities multiple breaks occur acro the width of the fault zone, all havi physiographic expression of recent su face displacement.

Throughout the length of this segm t of the fault zone, a number of faults splay eastward into the mountains (Fi 1c-e), and a few splay southward into the valley area (Fig. 1c). Near the northwest end of the map area (Fig. 1 is the confluence of the Punchbowl fa t (probably an ancient strand of the Sa Andreas) and the San Andreas fault. Near the middle of the map area (Fig. d the zone bifurcates into two major zo s --the north branch of the San Andreas (Mission Creek fault of Vaughan, 1922 Mill Creek fault of Allen, 1957) and e south branch (Dibblee, 1970, and this volume).

In addition to the splaying faults several faults are oriented at small

CORRELATION OF MAP UNITS

Qal	Holocene	QUATERNARY
Qoa₁	Pleistocene	QUATERNARY
	Pliocene (?)	TERTIARY
	Miocene	TERTIARY
	Paleocene (?)	TERTIARY
		CRETACEOUS
gn		PALEOZOIC OR OLDER
		PRECAMBRIAN (?)

DESCRIPTION OF MAP UNITS

Qal Alluvium; boulders in major stream channels

Artificial fill; compacted and uncompacted

Fill; colluvium, colluvial debris and slopewash

Major landslide deposits

Older landslide deposits; dissected deposits

Older alluvium, undivided; deposits of dissected unconsolidated to consolidated older alluvium

Locally divided onto:

Qoa₁ Unit 1; extensive fanglomerate along mountain front and extending up canyons. Consists of nearly planar, slightly dissected alluvial surfaces underlain by unconsolidated boulderly fanglomerate.

Unit 2; mainly older alluvial deposits of different ages along canyon sides above present level of deposition. Erosional surfaces developed on much of it.

Unit 3; highly oxidized reddish older alluvium, moderately indurated. Occurs as isolated patches along mountain front.

Nonmarine conglomerate and sandstone; includes maroon sandstone and conglomerate, brown gypsiferous fine-grained sandstone and siltstone and cream to tan arkose and arkosic sandstone in the Devore and Waterman Canyon areas, and tan, pink and dark-greenish-brown sandstone and conglomerate in the vicinity of and east of City Creek.

Punchbowl and Vaqueros (?) Formations of Woodburne and Golz (1972) Well indurated gray to pink arkosic sandstone and conglomerate.

San Francisquito (?) Formation of Woodburne and Golz (1972) Basal conglomerate of locally derived detritus overlain by well-bedded brown marine (?) sandstone and a few thick conglomerate beds

Granitic rock, undivided, quartz diorite to quartz monzanite af variable texture and structure.

Locally divided anta:

Biatite quartz manzanite; mainly massive leucocratic, equigranular biatite quartz manzanite; lacally parphyritic

Granadiorite, harnblende-biatite rich, slightly faliated and equigranular.

Harnblende-biotite granodiorite; locally porphyritic.

Quartz monzonite. Porphyritic biatite with large (± 2.5 – 5 cm) pink feldspar crystals.

Gneiss and granitic rocks; biotite-bearing gneiss with vorying amounts af faliated ta massive granitic rocks ranging from quortz diorite ta quartz manzanite. Locally includes lenses af caorse-grained morble

Pelana Schist; highly deformed greenschist, facies schist. Mainly spotted white mica-albite-quartz schist, chlarite schist and impure quartzite.

SYMBOLS USED

Contact

Fault showing dip. Solid where accurately lacated; dashed where approximately lacated ar inferred; datted where cancealed

Strike and dip of bedding

Strike and dip af vertical faliation

Strike ond dip of overturned bedding

Direction af londslide movement

Strike and dip af faliation

Fig. I a.

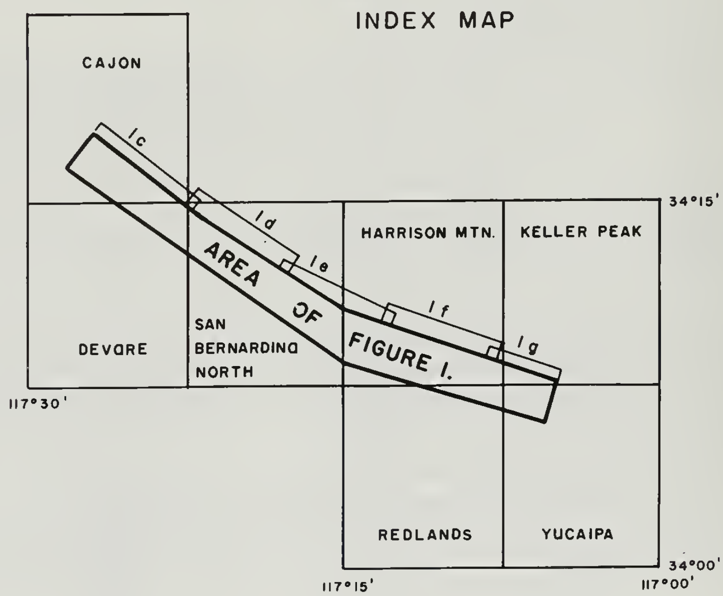


Fig. I b.

Fig. I c – I g. GENERALIZED GEOLOGIC MAP OF THE SAN ANDREAS FAULT ZONE NORTH OF SAN BERNARDINO.

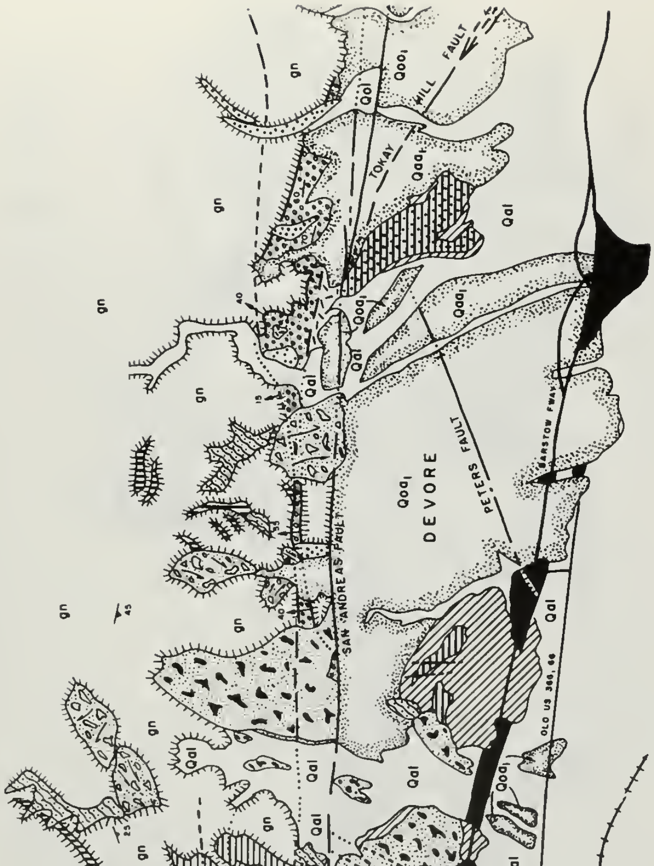
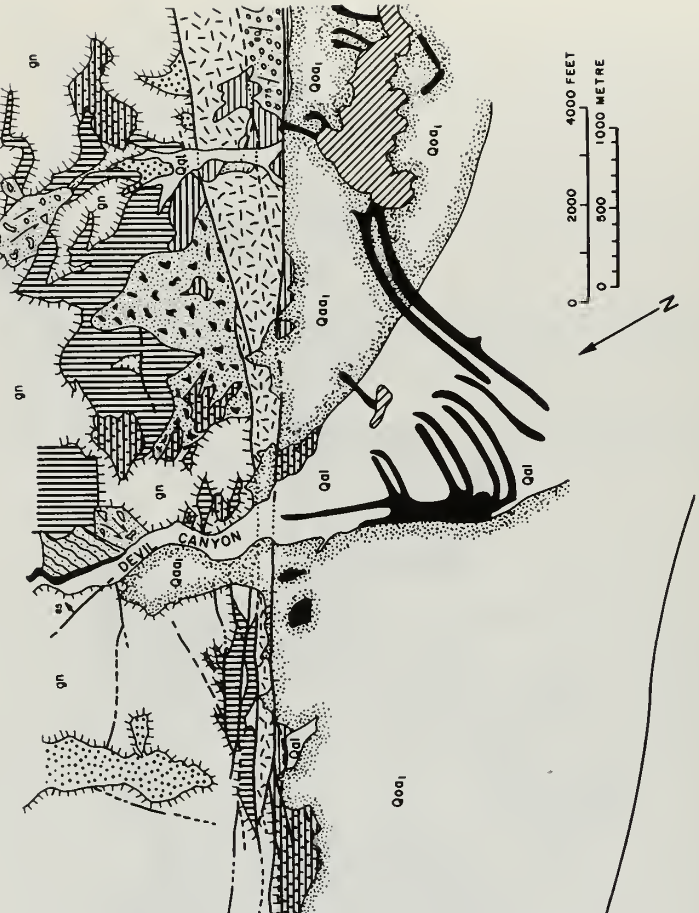

0 2000 4000 FEET
0 500 1000 METRE
N
SAN ANDREAS FAULT
PUNCHBOWL
FAULT
ZONE
CAJON CANYON
DEVORE
PETERS FAULT
TOKAY HILL FAULT
BARSTOW FWAY
OLD US 395, 66
ATCHISON TOPEKA AND SANTA FE
Qal
Qoa1
gn

Fig. 1c



DEVIL CANYON
CABLE CANYON
SAN ANDREAS
FAULT
BARSTOW FWAY
gn
Qal
Qoa_1
0 2000 4000 FEET
0 500 1000 METRE
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Fig. 1d

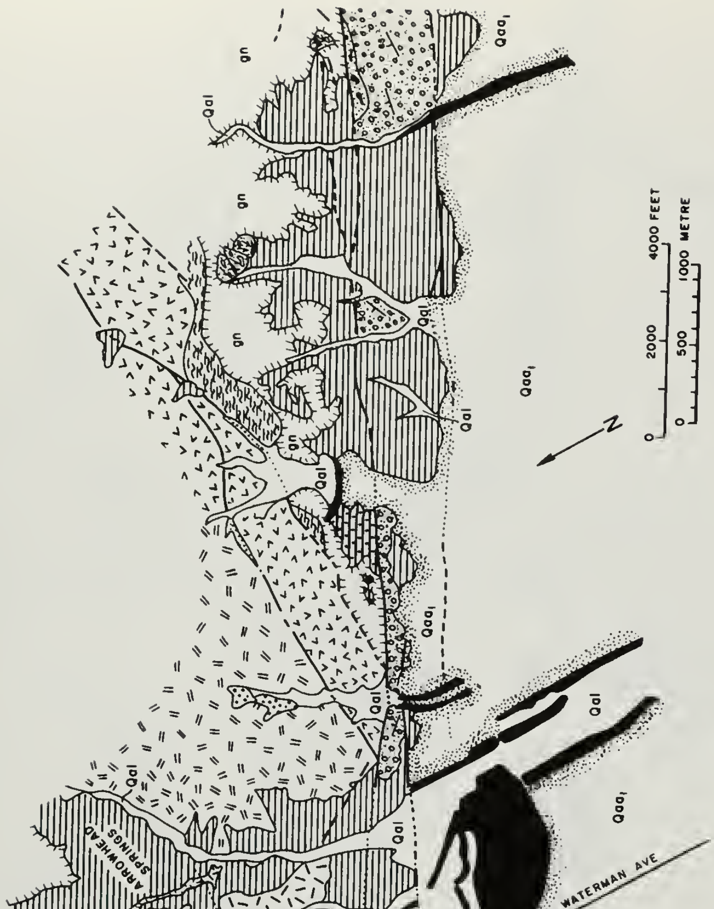
ARROWHEAD SPRINGS
WATERMAN CANYON
NORTH BRANCH SAN ANDREAS FAULT
SOUTH BRANCH SAN ANDREAS FAULT
WATERMAN AVE
gn
Qal
Qaa_1
N
0 2000 4000 FEET
0 500 1000 METRE

Fig 1e

SAN ANDREAS FAULT
NORTH BRANCH
SOUTH BRANCH
SAN ANDREAS FAULT
CITY CREEK
BOULDER AVE
HIGHLAND AVE
gn
Qal
Qoa_1
0
2000
4000 FEET
0
500
1000 METRE
N

Fig. 1f

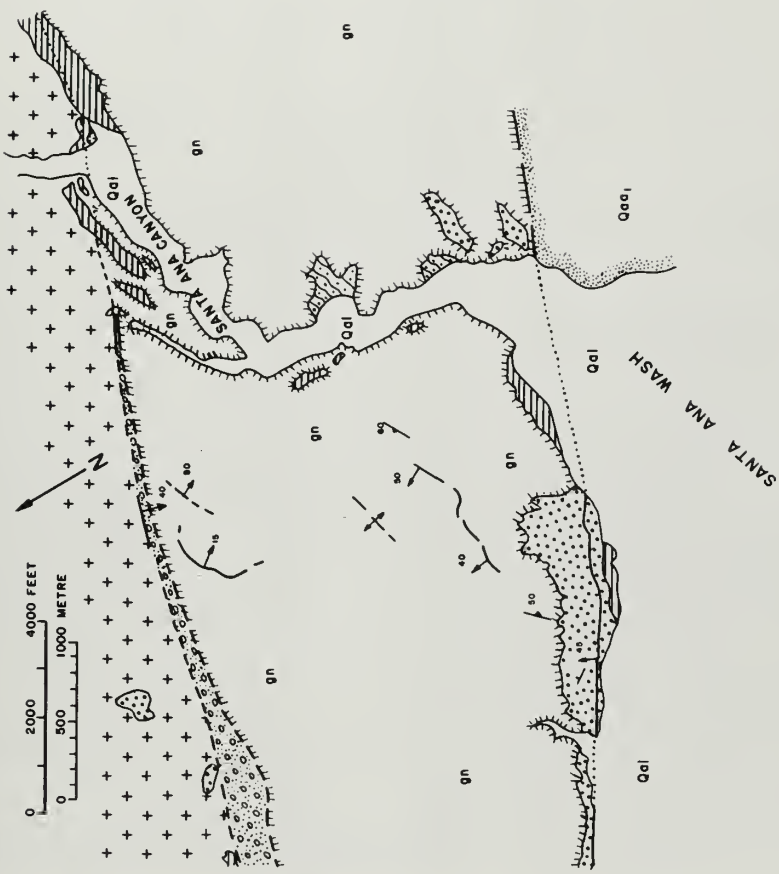
SANTA ANA CANYON
SANTA ANA WASH
Qal
Qaa1
gn
N
0
2000
4000 FEET
0
500
1000 METRE

Fig. 1g

high angles to the San Andreas (Fig. 1c). These faults occur both within and adjacent to the fault zone, and some of these also show evidence of recent surface displacement.

The San Andreas fault zone juxtaposes unlike basement rock types (see Dibblee, this volume) and contains remnants of once extensive Tertiary clastic sedimentary rock units and widespread older alluvial deposits.

SOME FEATURES OF THE FAULT ZONE

In the vicinity of Cajon Canyon (Fig. 1b), at the northwestern end of this segment of the fault, a wide variety of sedimentary clastic rocks occur as fault slices over a 1.5-km width (for a description of these rocks see Woodburne, this volume, and Woodburne and Golz, 1972, the nomenclature and age assignments of which are used herein). Here the sedimentary units include the Paleocene San Francisquito (?) Formation, the Miocene Vaqueros (?) and Punchbowl Formations (Woodburne and Golz, 1972), and unnamed clastic rocks. In this area the broad shear zone of the Punchbowl fault (up to a 300-m width of deformed gneiss and chloritic quartz diorite within the Pelona Schist) approaches the San Andreas and passes beneath the cover of an older landslide deposit at the inferred point of juncture (Fig. 1c). This older landslide deposit, well exposed on new freeway cuts (Barstow Freeway, U.S. 66, 395), has been right laterally offset at least several hundred metres by the San Andreas.

Three km southeast of where old U.S. 66, 395 crosses the San Andreas, the fault zone narrows to less than 1 km and the most deformed rock occurs in a zone 300 m wide. Typically the northern faults of the zone dip northward into the mountains at moderate to low angles with basement rock thrust over sedimentary units (Fig. 1c). To what extent these low dips can be attributed to the effects of gravity is unclear, but a reverse or thrust component of faulting is likely.

In the Devore area faults splay fro the San Andreas zone both to the east into the mountains and southerly towar the valley (Tokay Hill fault Fig. 1c). Located here is the east-striking Pete fault (Noble, 1954) which forms a nort facing scarp. Two faults that offset older alluvium are oriented normal to the San Andreas northwest of the Peter fault.

West of Waterman Canyon another maj splay of the San Andreas passes eastward through the vicinity of Arrowhead Springs (Fig. 1d, 1e). This fault has been mapped for 45 km eastward within e mountains (Dibblee, 1970). Further we 2 km west of Devil Canyon, the fault z e consists of an anastomosing complex wi a 500-m width. The fault zone bifurca s 1.5 km east of Devil Canyon into the n t and south branches (Fig. 1d). The two branches remain nearly parallel to the point where they cross City Creek (Fig f a distance of 13.5 km, east of which t two branches diverge. Except for the westernmost 1 km, sedimentary rocks li between the two branches eastward to t vicinity of City Creek. Eastward from City Creek the width of sedimentary ro progressively narrows (Fig.1f, 1g). The rocks are bounded on the north by the north branch and on the south by an unnamed fault that approaches the north branch near Plunge Creek and joins it Santa Ana Wash.

West of the City Creek both branche of the San Andreas fault have nearly continuous expression of primary surfa fault features (Fig. 2). East from City Creek, however, only the south branch shows primary surface fault features, although the north branch is well marked by the septum of included sedimentary rock. On both sides of City Creek urban developments are

Figure 2. View looking northwest along the San Andreas fault zone, north of San Bernardino. In the near foreground suburban development is extending across the scarps of the south branch of the San Andreas. In the background is the city of San Bernardino which extends onto the San Andreas fault zone. Scarps of the north branch of the San Andreas are located in the upper right corner and approach the south branch in the background. "See photo page 98"

rapidly obliterating or modifying some of the most spectacular scarps of this segment of the San Andreas fault (Fig. 2).

Landslides of various sizes occur throughout the length of the fault zone. Probably many of the larger landslides probably originated during earthquakes.

East of City Creek widespread dirt-filled fractures, extending to depths of 3 to 6 m beneath the surface, are locally seen in the crystalline rocks between the north and south branches. These cracks, oriented subnormal to the length of the ridges on which they occur, probably resulted from ground failures during past earthquakes. Thus, the process of secondary ground rupture between the two branches of the San Andreas poses a potential problem for future development.

ACKNOWLEDGEMENTS

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EN ECHELON FAULT PATTERNS OF THE SAN JACINTO FAULT ZONE

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ACT

e San Jacinto fault zone of southern ornia forms several en echelon fault rns among its member strands. The Helen-Claremont and Claremont-Casa fault pairs probably define zones of ow crustal extension or elongation th San Bernardino and San Jacinto ys, respectively. The Clark and e Creek faults between Anza and Bor- valleys bound a complex zone of cross uring within which right slip on the r fault has been transferred by al extension to the latter. Exposure is center of extension may be unique e San Andreas system.

OUCTION

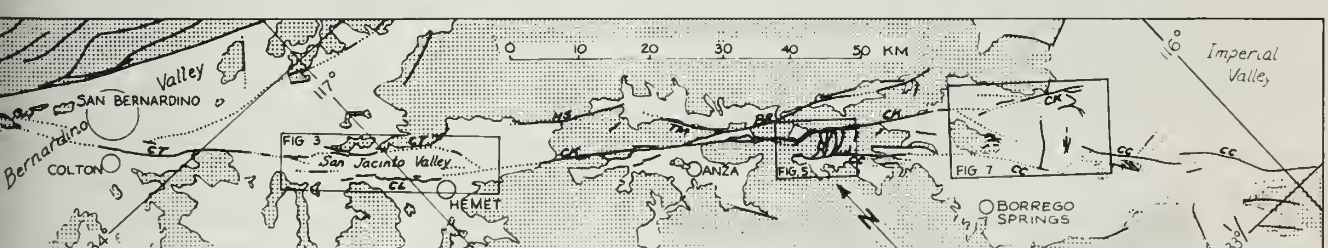
e San Andreas fault zone is straight ontinuous throughout much of its n in California, and these character- s are generally recognized as hall- of steeply dipping strike-slip s throughout the world. However, ce (1973) has emphasized that the s of most recent movement on the ndreas fault are commonly discontin- en echelon strands, the longest of are about 10-18 km. The overlap- en echelon strands are usually a fraction of a kilometer apart.

e San Jacinto fault zone, however, asts strongly with the San Andreas zone with respect to the continuity of its strands, despite the fact that the zone as a whole is fairly linear. Not only are en echelon fault relations more numerous along the San Jacinto fault zone, but also the length of individual strands arranged in en echelon pairs and the distance between the overlapping elements are both much larger than those described along the San Andreas. This paper concerns the pattern of en echelon faulting within the San Jacinto fault zone and describes several important relations of en echelon faulting that are not well illustrated elsewhere in the San Andreas system.

The traces of fault strands now recognized in the San Jacinto fault zone are shown in Figure 1. Because no single break appears to be clearly dominant or even continuous for the entire length of the zone, the different strands termed San Jacinto fault in many previous publications have been renamed as shown in the figure, and the name "San Jacinto" is herein applied only to the zone as a whole (Sharp, 1972).

EN ECHELON FAULT PATTERNS

Figure 2 portrays the relation of two right-slip fault strands that overlap to the right in an en echelon pattern. The overlap zone, defined by the fault traces and the dashed lines, represents an area of the earth's surface undergoing crustal extension or elongation parallel to the main faults (see arrows at the ends of



e 1. San Jacinto fault zone from San Bernadino Valley to western Imperial lley. Faults shown by heavy lines, dotted where concealed. Main fault members zone: GH, Glen Helen; CT, Claremont; CL, Casa Loma; HS, Hot Springs; CK, Clark; , Thomas Mountain; BR, Buck Ridge; CC, Coyote Creek. Stippled area: Mesozoic d older crystalline rocks; unstippled area: Tertiary and Quaternary sedimentary cks and alluvium.

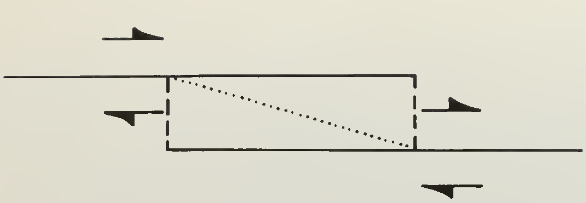


Figure 2. Diagram of overlapping en echelon faults. Solid lines are fault traces, dashed lines bound area of overlap, dotted line shows possible orientation of single fault at depth. Arrows show direction of relative movement.

the extensional area). This elongation and indeed the en echelon pattern itself may exist only in the shallow part of the earth's crust. At depths perhaps no greater than a few multiples of the surface distance between the en echelon breaks, the faults may converge downward into a single fault (represented in Fig. 2 by the dotted line diagonally crossing the area of elongation). The en echelon fault pattern therefore may be only a surface expression of a change in trend of the fault zone at depth to a direction more nearly north-south than the typical north-west trend.

Three major areas of known or suspected en echelon overlap exist along the San Jacinto fault zone. The three pairs of faults forming the en echelon patterns are the Glen Helen and Claremont faults in San Bernardino Valley (Fig. 1), the Claremont and Casa Loma faults in San Jacinto Valley (Fig. 3), and the Clark and Coyote Creek faults between Anza and Borrego valleys (Figs. 5 and 6). The two northern overlaps occur in alluvial areas, and because of sparse geological data on the details of faulting below the alluvial surfaces, they are only partly understood.

Glen Helen Fault - Claremont Fault Overlap

The Claremont fault is clearly the dominant trace of the San Jacinto fault zone immediately southeast of San Bernardino Valley, and surface expression of this trace is also spottily visible for about 6 km within the southern part of the valley (Sharp, 1972; Sieh and others, 1973). At the north edge of the valley, the zone apparently includes two major strands, nearly on line with the Claremont fault and the other, the Glen Helen fault, situated about 1.5 km to the northeast. Recent geologic mapping by D. M. Morton in the eastern San Gabriel Mountains indicates about 24 km of total right slip across the San Jacinto zone there, and this offset is divided about equally between the two strands (D. M. Morton, 19, pers. comm.). That such large displacement must be transferred entirely to one break at the south edge of the valley suggests, among other possibilities, an en echelon overlap. The fact that the Glen Helen fault shows scarps in young alluvium whereas the Claremont fault does not at the northern edge of the valley (Sharp, 1972) further suggests that transfer of displacement by crustal extension between en echelon fault pairs might be an expected feature in this area at the time of the next major earthquake. The next episode of surface movement may resolve whether there is simple bending or branching of the major trace to an unusual north-south trend or whether an overlapping en echelon fault relation exists.

Claremont Fault - Casa Loma Fault Overlap

The fault pattern within San Jacinto Valley seems to be a classic example of en echelon fault strands stepped to the right within a right-slip fault zone. Figure shows the linear graben-like structure

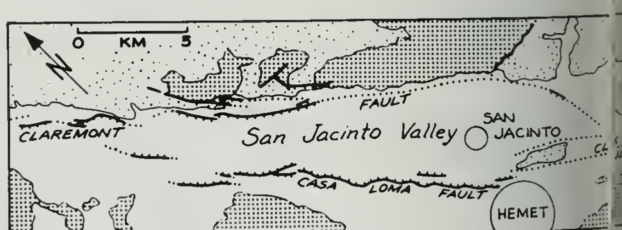
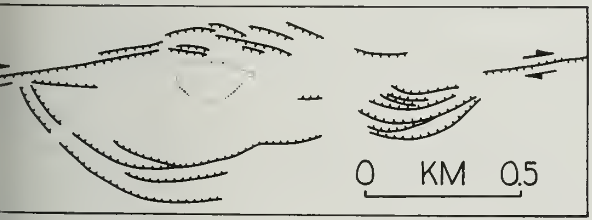


Figure 3. Fault pattern in San Jacinto Valley. Heavy lines are faults, hachures on downthrown sides. Dark stipple: Mesozoic and older crystalline rocks. Light stipple: Pliocene and Pleistocene continental sedimentary rocks. Unstippled areas: Quaternary alluvium. Location shown in Figure

ıcinto Valley, bounded on the north-
ɔy the Claremont fault and transected
: nearly parallel Casa Loma fault 3-5
the southwest. Although the trace
: latter fault is sinuous and has
nterpreted as a normal fault (Proc-
962), it does lie along the projec-
of the Clark fault which is clearly
ıjor right-slip fault strand within
ɔne to the southeast (Sharp, 1967).
ıe 24 km total right-lateral dis-
ıent established for the San Jacinto
zone (Sharp, 1967) is transferred
the Clark fault to the Claremont
is not obvious because of concealment
ıng alluvial cover on the floor of
ılley. Although other now-concealed
zones of distributed lateral slip
have absorbed the displacement, some
-lateral movement along the general
ıent of the Casa Loma fault may also
ɔccurred prior to the vertical off-
the valley floor. Near the surface
ıst, lateral displacement on the
ng faults probably has been trans-
l into northwest-southeast crustal
ıtion by normal faulting under the
for the length of the fault overlap,
ance comparable to the 24 km total
l offset for the fault zone. The
ry of concealed subsidiary frac-
within the en echelon overlap may
be known in detail, but it is inter-
to compare a similar fault pattern
the right-slip Hope fault in New
ıd (Clayton, 1966) shown in Figure 4.



e 4. Fault pattern on the Hope
ılt, New Zealand. Heavy lines are
ılt scarps, hachures on downthrown
le. Dotted line is outline of lake
bottom of central depression.
ıpted from Clayton (1966).

ɔpe fault analog is situated in
ıl outwash terrace deposits near the
River, South Island, and the fault
scarps have not been disturbed by younger alluviation since their formation. The analog suggests that the two relatively simple lateral shears break up into broad zones of multiple curving fault strands that converge on the opposite member of the en echelon pair. Although the dimensions of the New Zealand example are a little smaller, it is possible that a similar type of fracture pattern exists in the subsurface in San Jacinto Valley.

Clark Fault - Coyote Creek Fault Overlap

The overlap zone between the Clark and Coyote Creek faults is well exposed on the mountain ridge immediately northeast of Coyote Canyon (Fig. 5). Not only do fault

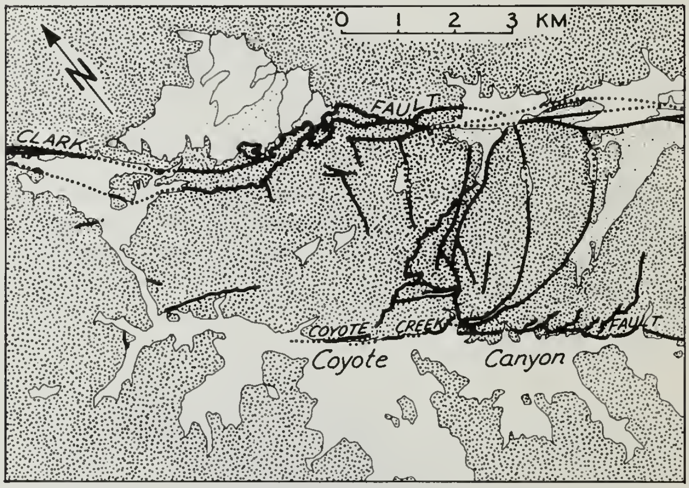


Figure 5. Fault pattern at northwest end of Coyote Creek fault. Heavy lines are faults. Location shown in Figure 1. Stippled areas same as in Figure 2.

relations on this ridge offer evidence for transfer of displacement between these major strands of the fault zone, but the ridge also reveals what may be a unique exposure of a crustal extensional zone between en echelon fault elements in the San Andreas system.

From the Coyote Creek fault near its northwest termination (Fig. 5), a complex group of strongly curved but generally northeast-trending faults extends across the ridge to the Clark fault. Movement within this group of cross-connecting fractures has allowed some of the right-lateral displacement on the Clark fault to be transferred by crustal extension to the Coyote Creek fault 4 km to the southwest. The amount of northwest-southeast crustal elongation probably has not exceeded about 2.5 km, the amount of net right slip on the northern part of the Coyote Creek fault (Sharp, 1967). In addition to the displacement on the large number of mapped breaks within the extensional zone, a large proportion of the total elongation may be distributed throughout the volume of rock involved, which is pervasively and intensely brecciated and sheared. Many of the faults within the extensional zone are doubly curved - that is, they curve both in strike and dip. At high elevations the breaks are mostly steeply-dipping normal and reverse faults, but the dips progressively flatten at lower elevations, and the structures become shallow-dipping normal faults. The curvature is convex to the southeast.

The probable net movement on the faults within the extensional zone and the bounding major faults is illustrated diagrammatically in Figure 6. From side to side

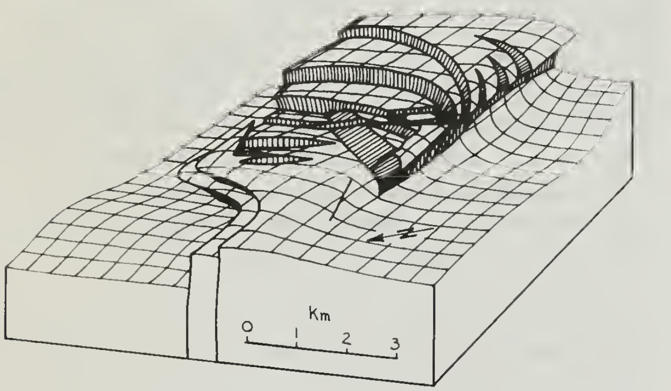


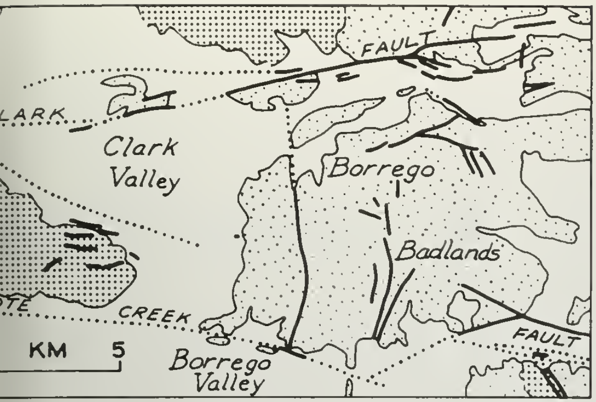
Figure 6. Diagrammatic sketch of crustal extensional zone between Clark and Coyote Creek faults. Location same as Figure 4. Clark fault cuts block on left, Coyote Creek fault on right. Fault surfaces are ruled with single direction (downdip) lines. An artificial reference surface ruled in two directions represents an originally horizontal surface now offset by faults and locally warped. Throw on individual faults is diagrammatic.

in the diagram, rocks between the bound faults are raised with respect to the outer blocks. From front to rear in th diagram, rocks generally rise stepwise across the extensional zone to the high level on the southeast side. The uniqu aspect of this zone of crustal extensic is its structural and topographic eleva tion relative to the surrounding areas. Generally, extensional zones between en echelon faults, such as the San Jacinto Valley example cited above and the deep linear basins in the Gulf of California (Rusnak and others, 1964), are marked b structural depressions and are filled w h a large volume of alluvium.

The en echelon pattern of the Coyote Creek and Clark faults separated by a zone of crustal elongation resembles th geometry proposed for crustal spreading centers between transform faults in oce anic basins. However, to label the Cla fault a transform fault with respect to the zone of crustal elongation would be somewhat inappropriate because the faul continues southeastward at least 40 km beyond the point of apparent spreading. Furthermore, whether the two en echelon faults remain separate at depths as gre as the base of the crust is unknown. [- vergence in strike of the two faults su gests that they probably become separat breaks at that depth farther to the sou- east, but it is highly probable that th extension described in this example is intracrustal.

FAULT PATTERN NEAR CLARK VALLEY

The fault pattern and distribution displacement between the Clark and Coyo Creek faults near Clark Valley (Fig. 7 show some features in common with the amples of en echelon faulting discusse above. Northwest of Clark Valley the Clark fault clearly has been the domin fracture in the San Jacinto fault zone (Sharp, 1967), but to the south the Co Creek fault apparently is the most act member of the zone. Bartholomew(1970) suggested that the line of major displ ment curves along the west side of Cla Valley and joins the Coyote Creek faul



7. Fault pattern near Clark
ley. Heavy lines are faults. Loca-
n shown in Figure 1. Stippled areas
e as in Figure 2.

uth. However, a detailed gravity near Coyote Mountain (W. J. Arabasz, ished data) and structural conti- of folds and faults in Borrego Bad- (Theodore and Sharp, 1975) indicate he fault on the west side of Clark dies out. Thus it does not appear that displacement on the southern f the Clark fault is transferred to uthern Coyote Creek fault by any connection of fault branches.

stal spreading seemingly could offer r explanation of apparent fault dom- n north and south of Clark Valley. Clark fault and the Coyote Creek bould another extensional zone of pe described for the same faults r northwest, then conceivably all lateral displacement could be trans- from the Clark fault to a center of l elongation located within or under rrego Badlands. However, geologic ure in the badlands indicates com- onal tectonics throughout this block, than northwest-southeast extension lore and Sharp, 1975). Extensional es could be concealed in Clark and in the 3-km-wide alluviated gap ately northwest of Borrego Badlands, e total amount of elongation there only be a small fraction of the net n the Clark fault. Unless the rocks d at the surface in the badlands are led in some manner from the under- lying crystalline basement, significant crustal extension does not seem to be applicable to this region.

Recent geologic mapping along the south- eastern part of the Clark fault indicates that complex branching and "horsetailing" into multiple strands are common. In ad- dition to the great complexity of fault relations, fold structures are intimately involved in the total deformation in that area. Mapping now underway will attempt to define the southeastward fate of the large displacement on the Clark fault.

ACKNOWLEDGMENTS

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ECTION 3

ajon Pass to Tejon Pass

to 4. San Andreas fault zone at Little Rock Creek, southeast of Palmdale, looking southeast. Mt. Emma Road in foreground; California aqueduct to left (northeast). Note offset streams, fault scarps, and fault ridges. J. S. Shelton Photograph No. 6855, 24 Nov. 1974, 8500 ft. elevation.

Photo 5. Looking east at deformed Pliocene beds of Anaverde Formation within the San Andreas fault zone. The active fault today crosses the freeway adjacent to the roadcut on the right (south, just out of the photo).
Air photograph by W. Roy Watson, 1972

Photo 6. Detail from center of roadcut shown in photo 1. Note that the ground surface is apparently displaced by this "active" fault, and that a smal graben (skyline) has resulted. Photograph by Richard G. Shaw, 1971

TECTONICS OF THE WESTERN MOJAVE DESERT NEAR THE SAN ANDREAS FAULT

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ACT

e western Mojave Desert near the San as fault is largely an alluviated underlain by Mesozoic granitic . Gravity data reveal three east- east-trending basins of Cenozoic nic and sedimentary rocks on down- d parts of the granitic surface, ated by two gravity highs with scat- outcrops of granitic rocks. The rn and eastern basins each expose 2670 m (8,000 ft) of Cenozoic de- s near the San Andreas fault. al movements that formed these s in large part ceased probably in e Pleistocene time within the desert re continuing along its margins in orm of uplift by lateral drag move- along the San Andreas and Garlock zones.

DUCTION

is report summarizes the regional gy of the western Mojave Desert and near the 140 km (90 mi) segment e San Andreas fault from Quail Lake Gorman) to Cajon Pass, primarily the author's own mapping and inter- tions recorded in earlier reports egional maps (Dibblee, 1967, 1968, . References to more detailed gic maps are listed therein and in os Angeles and San Bernardino Sheets e Geologic Map of California ings and Strand, 1969; Rogers, 1969).

GIC SETTING AND MAJOR ROCK UNITS

e western Mojave Desert is a high, iated plain that slopes northward the mountains elevated along the San as fault at its southwestern border outheastward from the Tehachapi ains elevated along the Garlock at its northwestern border. The major rock divisions of the west- ojave Desert are: (1) pre-Tertiary crystalline basement complex of plutonic and metamorphic rocks, (2) Tertiary volcanic and sedimentary rocks, and (3) Quaternary alluvial deposits.

The pre-Tertiary basement complex is a granitic batholith of predominantly quartz monzonite-granodiorite composition of Mesozoic (Cretaceous) age. It is largely buried under the desert plain but crops out at Antelope Butte, Alpine and Lovejoy Buttes and vicinity, and along the margins elevated near the San Andreas and Garlock faults (figs. 1, 2).

In the Tehachapi Mountains (fig. 1) the batholithic rocks contain pendants of metasedimentary rocks of Paleozoic(?) age. In the Table Mountain area near the San Andreas fault (fig. 2) the batholithic rocks are intrusive into north-dipping marble-bearing gneiss (Precambrian?). Portal Ridge on the north side of the San Andreas fault west of Palmdale (fig. 1) is eroded from a narrow slice of Pelona Schist (Mesozoic or older).

The granitic batholith that underlies the western Mojave Desert is juxtaposed along the San Andreas fault against a basement complex to the south composed of Precambrian gneissic rocks intruded by a variety of plutonic rocks of Precambrian to Cretaceous age. All these rock units are separated by an interval of mylonite from, and may be allocthonous to, the structurally underlying Pelona Schist that is anticlinally folded near the San Andreas fault (figs. 1, 2).

The deeply eroded surface of the granitic batholith of the western Mojave Desert near the San Andreas fault is overlain by a sequence of volcanic and terrestrial sedimentary rocks of middle and late Tertiary age. In areas where this surface was downwarped this sequence is very thick. Where exposed, this sequence is deformed, especially near the San Andreas fault; elsewhere it is covered by Quaternary alluvial deposits, which in most parts lap unconformably over this sequence onto the granitic bedrock of the elevated areas. The Tertiary rocks are exposed mainly in three areas (figs. 1, 2) as follows (Dibblee, 1967):

1. In the west Antelope Valley area (figs. 1, 3), the lower part of the sequence is a rhyolitic and andesitic volcanic unit (Neenach Volcanic Formation, Oligocene(?) and early Miocene) overlain by a terrestrial sedimentary unit as thick as 1,600 m (5,000 ft) of granitic and volcanic detritus (Oso Canyon Formation, Late Miocene). This terrestrial unit overlies a marine facies of sandstone and shale (Quail Lake Formation) only in the western part of this area. The terrestrial and volcanic rocks of this sequence, which accumulated in an extensive basin, are probably continuous under west Antelope Valley to exposures in Antelope Buttes and the Rosamond Hills. This is the only basin in the western Mojave Desert near the San Andreas fault known to contain volcanic rocks.

2. In a strip about 45 km (30 mi) long between the San Andreas fault and the unnamed parallel fault less than 1 km (1 mi) north (figs. 1, 2), the sequence (Anaverde Formation, Pliocene, described eleswhere in this volume) may be as thick as 660 m (2,000 ft) and is composed of terrestrial strata of granitic detritus, with lacustrine clays and gypsum in the upper part.

3. In the Cajon Pass area (fig. 2), the lowest Tertiary unit is a small remnant of a highly indurated marine sedimentary formation, (Paleocene?). The remainder is a sequence as thick as 2,300 m (7,000 ft) of terrestrial strata of Miocene and Pliocene age that includes at the base a thin marine lens (Vaqueros Formation, early Miocene). See Woodburne, this volume, for a detailed description of these units.

Quaternary alluvial sediments that cover the western Mojave Desert near the San Andreas fault were derived primarily from the mountains across south of the fault and deposited as a northward-sloping alluvial apron, which is highest and coarsest near the high eastern part of the San Gabriel Mountains (fig. 1). At Cajon Pass the highest part of this alluvial apron, where the Pleistocene gravels of this apron were elevated an tilted slightly northward, was removed by headward erosion of the southward-draining system of Cajon Creek.

REGIONAL GEOLOGIC STRUCTURE

The isolated low hills and buttes o granitic rocks, such as Antelope Butte (fig. 1) and Alpine and Lovejoy Buttes (fig. 2) within the western Mojave Dese plain, are remnants of probably once mountainous terranes of granitic rocks elevated in late Tertiary or early Qua-ternary time, and subsequently reduced to low relief or peneplaned. The larg intervening alluviated areas are probaly structural basins or downwarps of Cenoz sedimentary deposits, as indicated by regional geophysical survey (Mabey, 19). During late Quaternary time this deser region appears to have been in large part stabilized, but the margins adjac to the San Andreas and Garlock faults (figs. 1, 2) continued to be affected crustal movements to form low mountain or hills by faulting, arching, and til ing, presumably as lateral drag effect on the San Andreas and Garlock faults, exposed the basement and overlying Ter-ary rocks.

A gravity survey of the western Moj Desert indicates that north of the San Andreas fault this desert plain contai three large basins filled with low-density sedimentary and volcanic rocks to estimated depths of about 3,300 m (10,000 ft) separated by areas of rela-tively high gravity basement rocks at near the surface (Mabey, 1960; Dibble 1967, p. 111-113). The basins are elo-gated northeastward or eastward, paral to the Garlock fault, and at least tw of them extend to the San Andreas fau (figs. 1, 2). As shown, West Antelop basin underlies West Antelope Valley d parallels the Tehachapi Mountains to e northwest. The Tertiary sequence of i basin crops out near the San Andreas fault north of Liebre Mountain (figs. , 3; Dibblee, 1967, p. 61) where it is severely deformed. East Antelope bas nds northeastward from Lancaster . 1). The Tertiary(?) rocks of this n do not crop out. Cajon basin rlies the desert plain north of Cajon . The Cenozoic sediments of this n crop out on its south flank south ajon Pass (fig. 2; Dibblee, 1967, 4, Woodburne, this volume), where are much deformed.

he segment of the marginal uplift h of Antelope Valley (fig. 1) exposes granitic basement along its major . North of Liebre Mountain this is lain by, and is in part thrust north- against, the 2,700 m (8,000 ft) k middle Tertiary volcanic and sedi- ary sequence of West Antelope basin; e exposed, this sequence is tightly ressed into east-trending folds (fig. ibblee, 1967, p. 59). Southeastward granitic uplift is in contact along Hitchbrook fault with the north- ing Pelona Schist of Portal Ridge . 1). This ridge and the low itic exposure near Palmdale and lerock are separated from the San eas fault to the south by a narrow e of the Anaverde Formation, which n part tightly compressed into a ine (Dibblee, 1967, p. 57).

he low granitic uplift near Palmdale Littlerock, which terminates against ult southeast of Pearblossom (fig. is narrow in outcrop but may extend heastward under the alluvium of the rt plain to the granitic exposures of Alpine and Lovejoy Buttes area, as ested by gravity data (Mabey, 1960; lee, 1967, p. 112).

he major marginal uplift of basement lex that includes Table Mountain on north side of the San Andreas fault verlain by the Crowder Formation ocene) and Quaternary gravel, both hich are tilted northward (fig. 2). of Wrightwood this uplift is elevat- n the Cajon Valley fault against the led but generally north-dipping so- ed Punchbowl Formation (Miocene) of n Canyon; to the northwest the der Formation overlaps this fault onto the basement complex of this uplift (fig. 2; Dibblee, 1967, p. 52, 54).

LATERAL DISPLACEMENTS ON STRANDS OF THE SAN ANDREAS FAULT SYSTEM

The San Andreas fault system that borders the western Mojave Desert bears about N 65° W and is a single active main strand marked by scarplets, small ridges, sag ponds, and offset stream channels. All these features are the effects of late Quaternary right-slip movements on this fault. Post-Oligocene cumulative right-slip of about 280 km (130 mi) has been postulated (Crowell, 1962, p. 36, 43, 44, 50) presumably on this main strand.

On the lesser inactive strands north of the main strand, the amount of strike-slip movement if any, is not known, but the vertical displacements of those that elevate basement rocks against Cenozoic deposits (figs. 1, 2) are well defined. On the now inactive Nadeau and Punchbowl faults, which are the major southern strands of the San Andreas fault system, the anticlinally folded (Pelona) schist of Blue Ridge (figs. 1, 2) may be displaced nearly 48 km (30 mi) southeastward from that of Sierra Pelona (Dibblee, 1967, p. 114; 1968, p. 264-265). The Punchbowl fault is not part of the San Jacinto fault, as commonly thought, but is a strand of the San Andreas fault that joins the main strand east of Cajon Creek.

In the Cajon Canyon area northeast of the San Andreas fault, the Paleocene(?) marine unit and the middle Tertiary Vaqueros and "Punchbowl" Formations (fig. 2) may be displaced about 150 km (95 mi) from similar rock units exposed in the Cuyama Badlands--east Caliente Range area on the southwest side of the fault (Dibblee, 1975; fig. 4).

In the west Antelope Valley area northeast of the San Andreas fault, the middle Tertiary Neenach Volcanic Formation, Quail Lake, and Oso Canyon Formations (fig. 1) may displaced 150 to 255 km (95 to 160 mi) from similar rock units

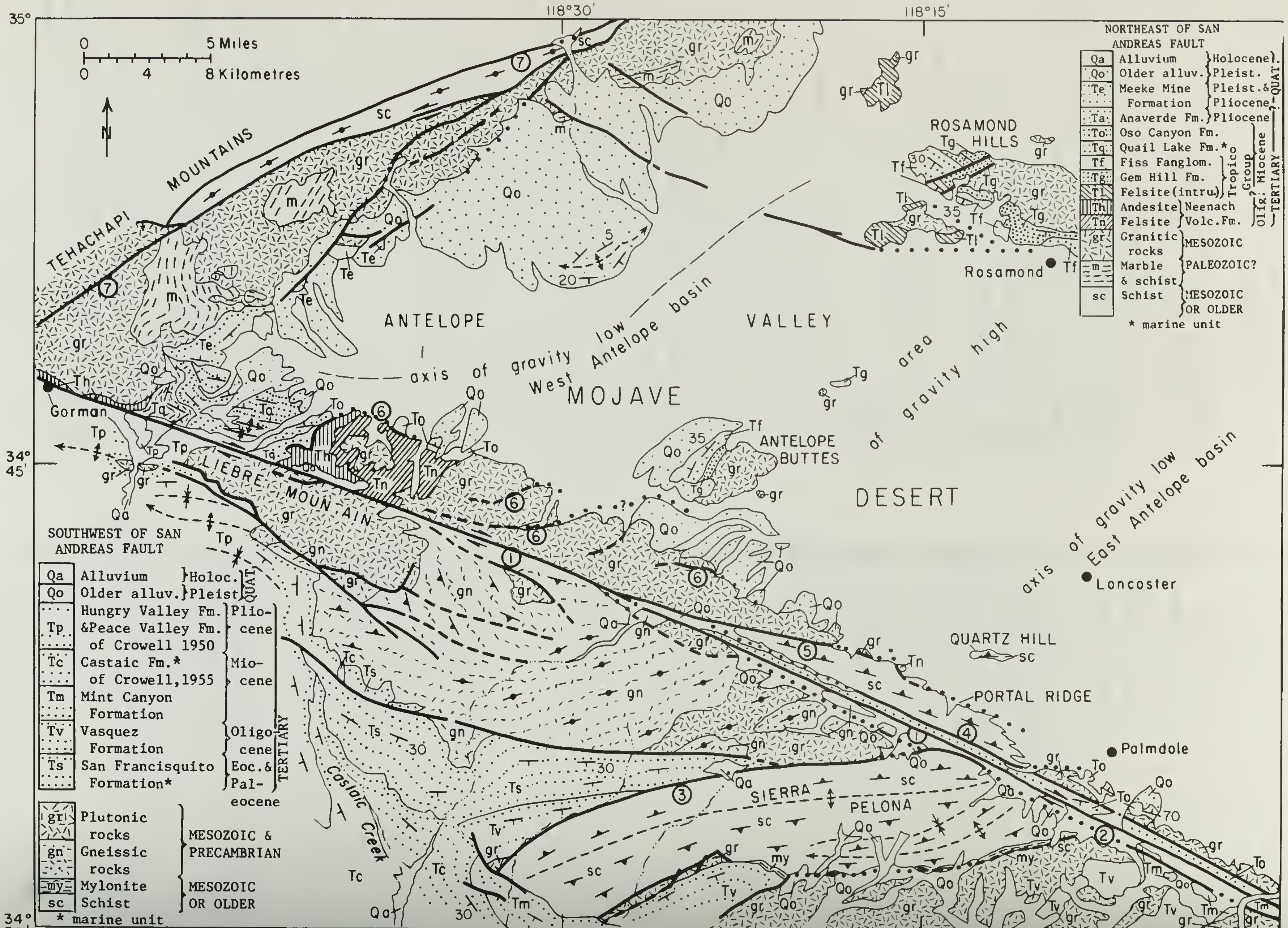

Figure 1. Geology along the San Andreas fault from Gorman to Palmdale and adjacent mountain and Mojave desert areas. Modified from Geologic map of California, Los Angeles sheet (Jennings and Strand, 1969). Major faults as follows: 1, San Andreas (active); 3, San Francisquito; 4, unnamed; 5, Hitchbrook; 6, unnamed thrust faults; 7, Garlock.

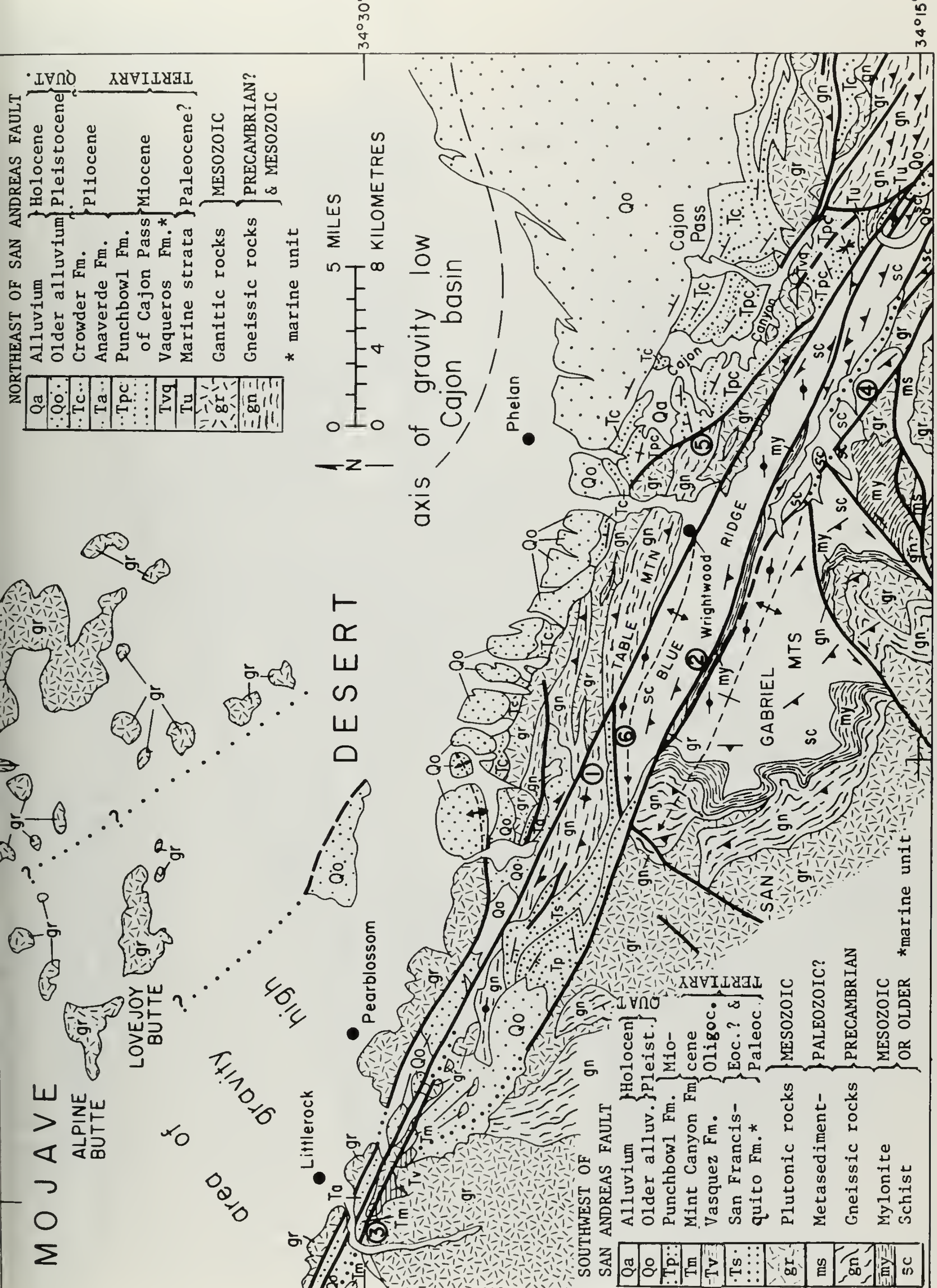

Figure 2. Geology along the San Andreas fault from Littlerock to Cajon Pass. Generalized from Dibblee (1970). Major faults as follows: 1, San Andreas (active); 2, Punchbowl; 3, Nadeau; 4, San Jacinto; 5, Cajon Valley; 6, Fenner.

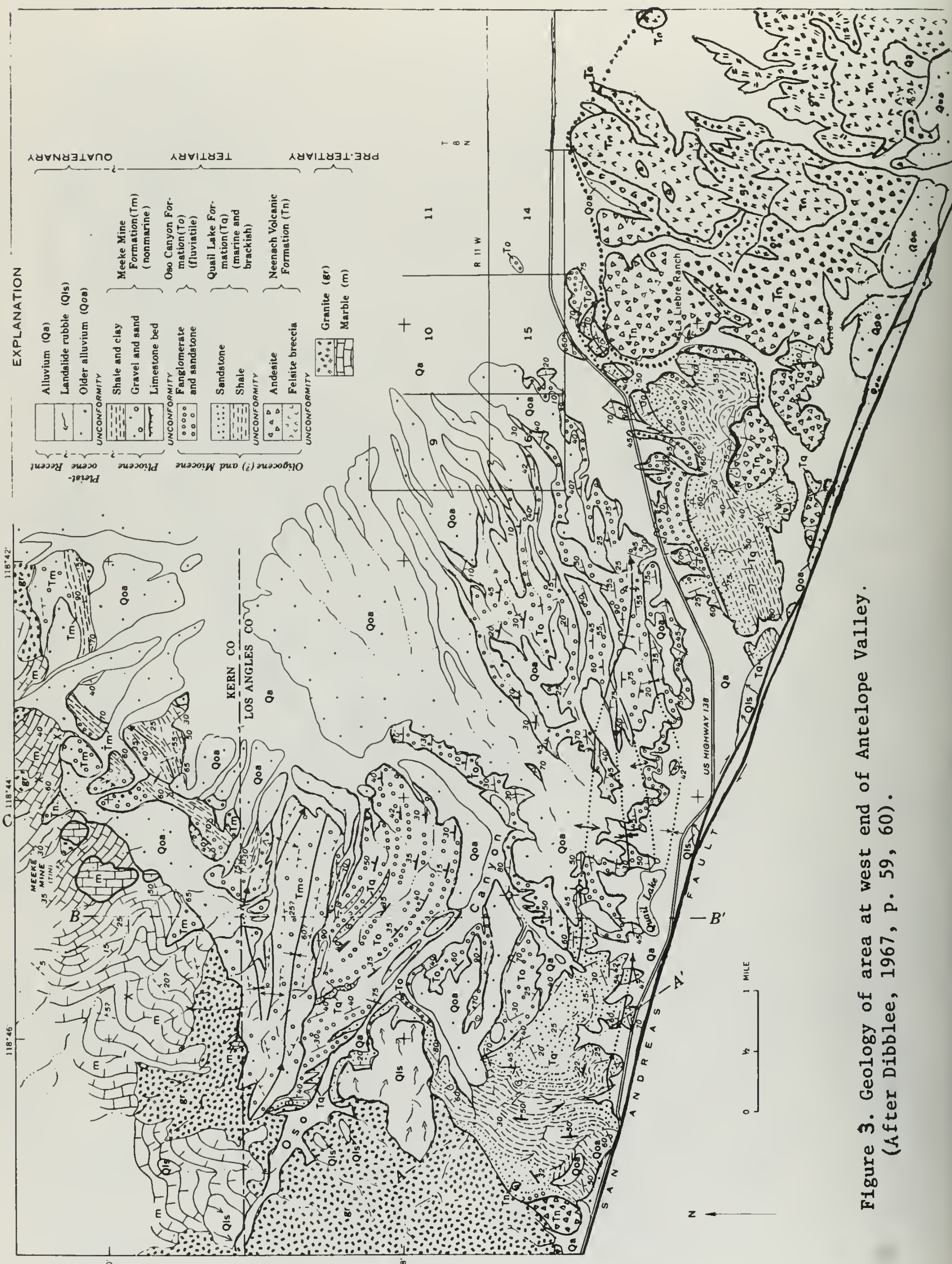

Figure 3. Geology of area at west end of Antelope Valley. (After Dibblee, 1967, p. 59, 60).

ween the north Carrizo Plain and the
nacles area of the Gabilan Mountains
the southwest side of the fault
oblee, 1975; fig. 4).

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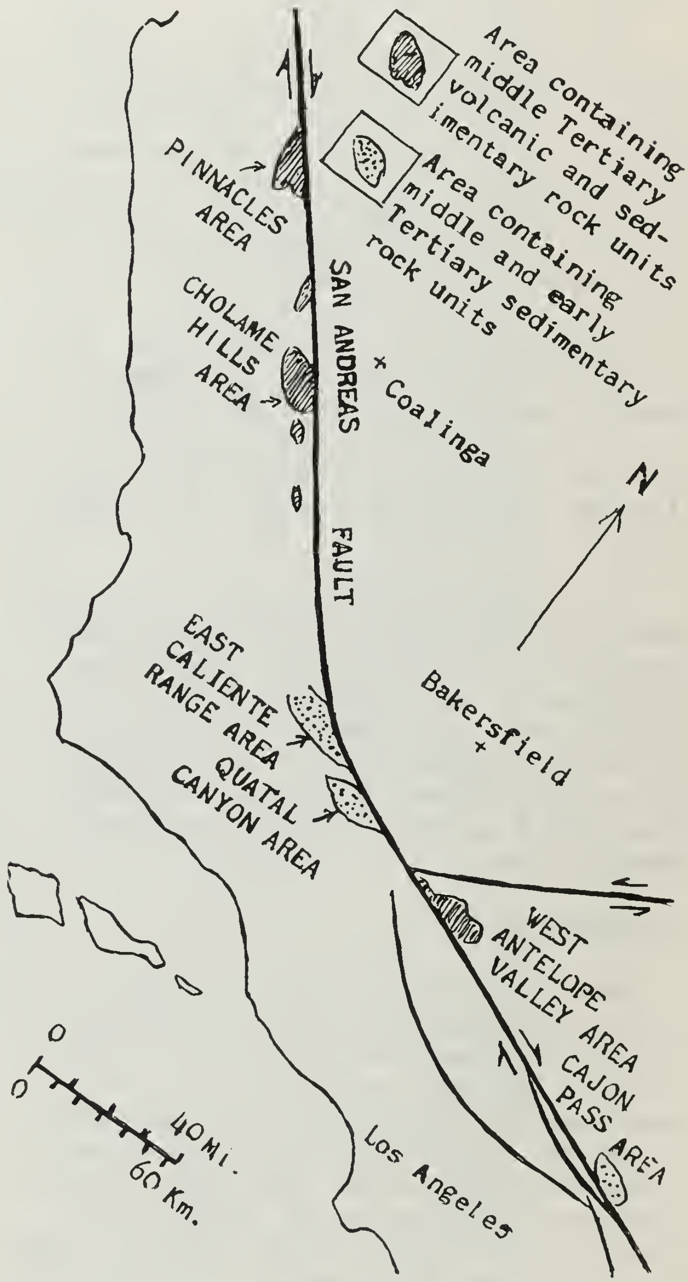

Figure 4. Areas of similar Tertiary rock units possibly separated by large amounts of right slip on San Andreas fault.

SEDIMENTOLOGICAL AND TECTONIC IMPLICATIONS OF THE PALEOCENE SAN FRANCISQUITO FORMATION, LOS ANGELES COUNTY, CALIFORNIA

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ABSTRACT

Strata of the Paleocene San Francisquito Formation exhibit sedimentologic features characteristic of 1) deposition of coarse clastic material on southwesterly trending submarine fans and 2) deposition of fine-grained clastic material by turbidity currents along a northwest-southeast trending ocean basin.

Previous workers have documented approximately 50 kilometers of movement between Sierra Pelona and Blue Ridge terrain along the Nadeau and Punchbowl faults. Similarity of Paleocene strata in the two regions also supports 50 kilometers of displacement.

The above documented offset along the Nadeau and Punchbowl faults, and Paleocene sedimentation history suggest that Paleocene or pre-Paleocene activity on the San Andreas fault system, in the central Transverse Ranges was either non-existent or of a considerably smaller magnitude than shown by offsets from late Miocene to Recent time.

INTRODUCTION

Reconstruction of the tectonic evolution of southern California is often obscured because of a lack of data. This lack of data has resulted in continuing controversy regarding total displacement along the San Andreas fault system and time of initiation of faulting. North of the Transverse Ranges of southern California, displacement along the San Andreas fault system is estimated to be about 530 kilometers, with movement beginning sometime around the Cretaceous-Tertiary transition (Wentworth, 1968). However, in southern California, total displacement is estimated to be about 300 kilometers, beginning sometime in late Miocene time (Crowell, 1973). If a pre-Miocene San Andreas fault existed in the Transverse Range area, then study of pre-Miocene strata near the present fault system might present new data for resolving th above displacement and timing discrepancies.

Paleocene sedimentary rocks were stu ied in the Big Rock Creek area adjacent to Devils Punchbowl, and in the Bouquet Reservoir-Fish Canyon area, about 8.0 kilometers north of Saugus (Fig. 1). Special emphasis was placed on determin ing Paleocene geography and sedimentatin trends in order to evaluate whether the data would aid in resolving the questic of fault movement during Paleocene time in the central Transverse Ranges.

LITHOLOGY

Dibblee (1967) assigned Paleocene strata in the above localities to the n Francisquito Formation. These strata - conformably overlie Precambrian (?) gneiss and are in turn overlain by Mio cene sedimentary rocks (Fig. 1).

The San Francisquito Formation in t Big Rock Creek area includes breccia, shale, sandstone, and conglomerate facies (Figs. 2 and 3). The breccia facies cn sists of irregularly distributed cobbl to-boulder gneiss breccia resting in a deformed shale matrix along the Paleocne Precambrian (?) unconformity on Pinyon Ridge. The shale facies comprise shal with subordinate sandstone which grade northwest into a thick-bedded sandstor facies. These facies progressively over lap underlying gneiss, forming a "buttress" unconformity along Pinyon Ridge The conglomerate facies is best expose in Big Rock Creek and grades northwest and southeast into the thick-bedded sand stone facies.

The San Francisquito Formation, fro Bouquet Reservoir to Fish Canyon compr e shale, sandstone, and conglomerate fa e

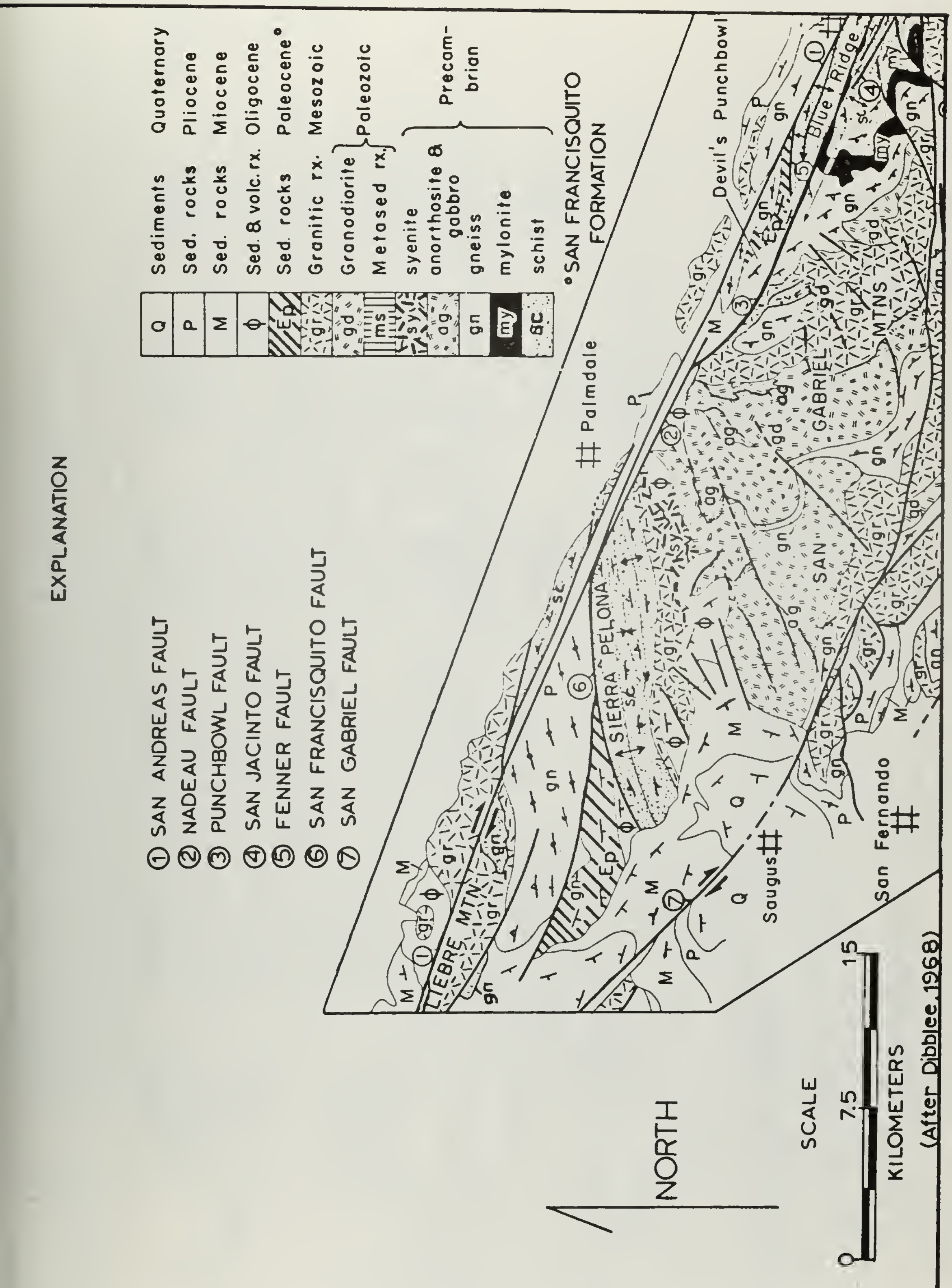

Figure 1. Geologic map of the Sierra Pelona and Blue Ridge areas, California.

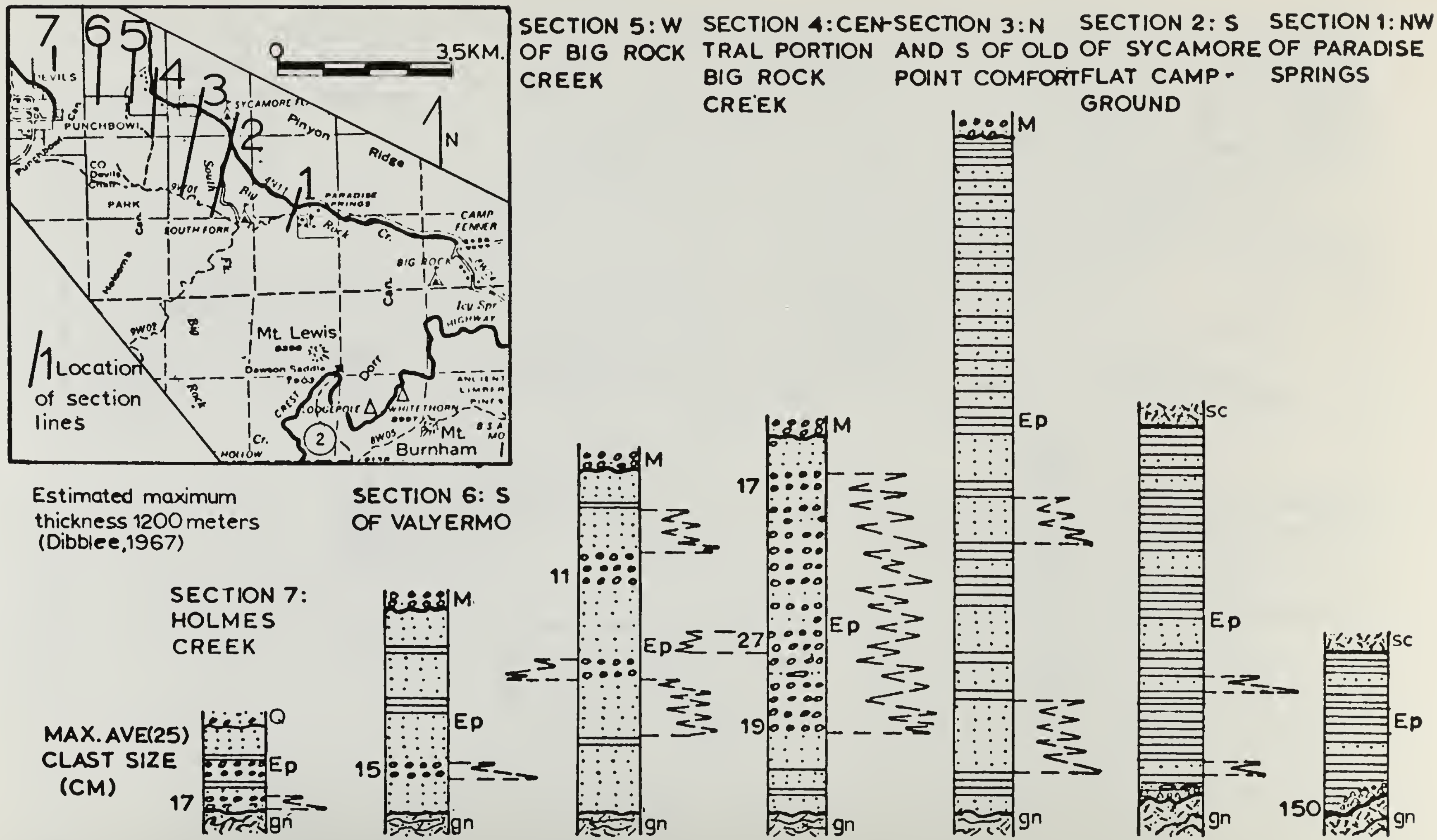

Figure 2. Stratigraphic sections and vicinity map San Francisquito Formation, Big Rock Creek area.

LITHOLOGY	Shale facies: poorly bedded, moderately indurated, carbonaceous shale; interbedded, moderate-to poorly sorted, fine-to coarse-grained sandstone. Sandstone facies: thick-bedded, moderately indurated, poorly sorted, medium-to very coarse-grained sandstone; subordinate carbonaceous shale. Conglomerate facies: thick-bedded, lenticular, well indurated, poorly sorted, pebble-to boulder-conglomerate, subordinate thick-bedded, lenticular, well indurated, very coarse-grained sandstone.	Breccia facies: poorly bedded, poorly sorted, cobble to boulder breccia; deformed shale matrix. Shale facies: thin-bedded, moderately indurated carbonaceous shale and subordinate thin-bedded well indurated, moderately sorted, fine-to medium-grained sandstone. Sandstone facies: thick-bedded, well indurated, poorly sorted, medium-to coarse-grained sandstone; subordinate dark-gray shale. Conglomerate facies: thick-bedded, lenticular, well indurated, poorly sorted, pebble-to boulder conglomerate; subordinate lenticular, well indurated, poorly sorted, very coarse-grained sandstone.
SEDIMENTARY STRUCTURES	Shale facies: Complete Bouma sequences in thin-bedded sandstones. Sandstone facies: Bouma a-b-a and a-b-e intervals, flute casts. Conglomerate facies: pebble imbrication, lenticular channels, scour marks, graded bedding, rounded clasts.	Shale facies: complete Bouma sequences in thin-bedded sandstones. Sandstone facies: Bouma a-b-e intervals, groove casts. Conglomerate facies: pebble imbrication, lenticular channels scour marks, graded bedding, rounded clasts.
PALEOCURRENT AVERAGES	Pebble imbrication: south-southwest Flute casts: south-southwest Small-scale crossbedding: southeast, northwest, south-southwest	Pebble imbrication: south-southwest Groove casts: northeast-southwest trend Small-scale crossbedding: southeast
FOSSILS	In situ fossils at base of section along unconformity: Turritella pacheocoensis Stanton, Turritella infragranulata Gabb, Crassatellites branneri Waring, Glycimeris major Stanton. Abraided thick-shelled mollusks in conglomerate and sandstone facies, planktonic foramini fera in Shale facies.	In situ fossils at base of section along unconformity: Turritella pachecoensis Stanton, Venericardia sp., Glycimeris sp., Turritella infragranulata Gabb, Crassatellites sp., Amauropsis martinezensis Dickerson. Abraided thick-shelled mollusks in Conglomerate and Sandstone facies.

Figure 3. Sedimentologic features of the San Francisquito Formation.

(Figs. 3 and 4). The shale facies consists of shale and subordinate sandstone which grade northwest into a thick-bedded sandstone facies. Both of the above facies progressively overlap the gneiss contact forming a "buttress" unconformity. The conglomerate facies is best exposed in Fish Canyon and grades rapidly southeast into the sandstone facies.

PALEOCURRENT FEATURES

Paleocurrent data (Fig. 5A) were obtained from pebble imbrication of ellipsoidal conglomerate clasts, flute casts, groove casts and small-scale cross bedding (less than 5 centimeters in height). The above features were difficult to locate and measure because of impenetrable chapparral obscuring exposures. Data were therefore obtained from outcrops in stream canyons and along trails and roadcuts. Fortunately, these exposures were interspersed throughout each locality thus assuring statistically significant measurements that are representative of average paleocurrent trends. Paleocurrent averages are summarized in Figure 3.

PALEOGEOGRAPHY

The depositional environment for the San Francisquito Formation is postulated to be a submarine fan-basin floor complex (Fig. 5B). Based upon paleocurrent data, facies changes, and sedimentary structures, it is envisioned that clastic materials were deposited on the submarine fans while sands were carried into a basin by turbidity currents. Muds were deposited from suspension. In the Big Rock Creek area local accumulations of breccia were derived from irregular topographic highs along the depositional interface.

Since the two San Francisquito Formation localities lie within the San Andreas fault system it is necessary to ascertain whether or not these strata are presently in the same geographic position as when deposition occurred. Dibblee (1968) postulated about 50 kilometers of displacement along the Nadeau and Punchbowl faults in late Pliocene or Pleistocene time (Fig. 1). This offset was based o matching geology in the Sierra Pelona a Blue Ridge areas. The close lithologic and sedimentologic similarities between the San Francisquito Formation in the B Rock Creek and Bouquet Reservoir-Fish C yon areas suggest the rocks were probab deposited within the same or closely ad cent basins. Their present geographic distribution is thus attributed to post Paleocene movement of approximately 50 kilometers along the Nadeau and Punchbo faults within the San Andreas system.

Sedimentation trends of the above Paleocene strata can be used to determine whether or not a Paleocene or pre-Paleocene San Andreas fault was active in th San Francisquito Formation region. The following data suggest that the San Andreas fault in the above region, was either inactive from Precambrian (?) to the end of Paleocene time or fault activity was of a considerably smaller magn tude than commonly inferred from late Miocene to Recent time. 1) Precambrian (?) gneiss appear to be offset the same distance as Paleocene San Francisquito Formation. 2) Exposures of San Francis quito Formation consist of an orderly distribution of facies consistent with deposition in a submarine fan-ocean bas complex. In contrast, sedimentary depc its such as the Violin Breccia which we deposited from scarps adjacent to the active San Gabriel fault of the San And as fault system (Crowell, 1973) do not have the above orderly distribution of facies. 3) Breccia at the Paleocene-Pr cambrian (?) contact on Pinyon Ridge dcs not appear to have emanated from an act fault scarp as the breccia is not exter sive laterally, and is absent along muc of the contact. In addition, the brecca is not present in the Fish Canyon-Warm Springs Mountain area along the Paleoce Precambrian (?) contact.

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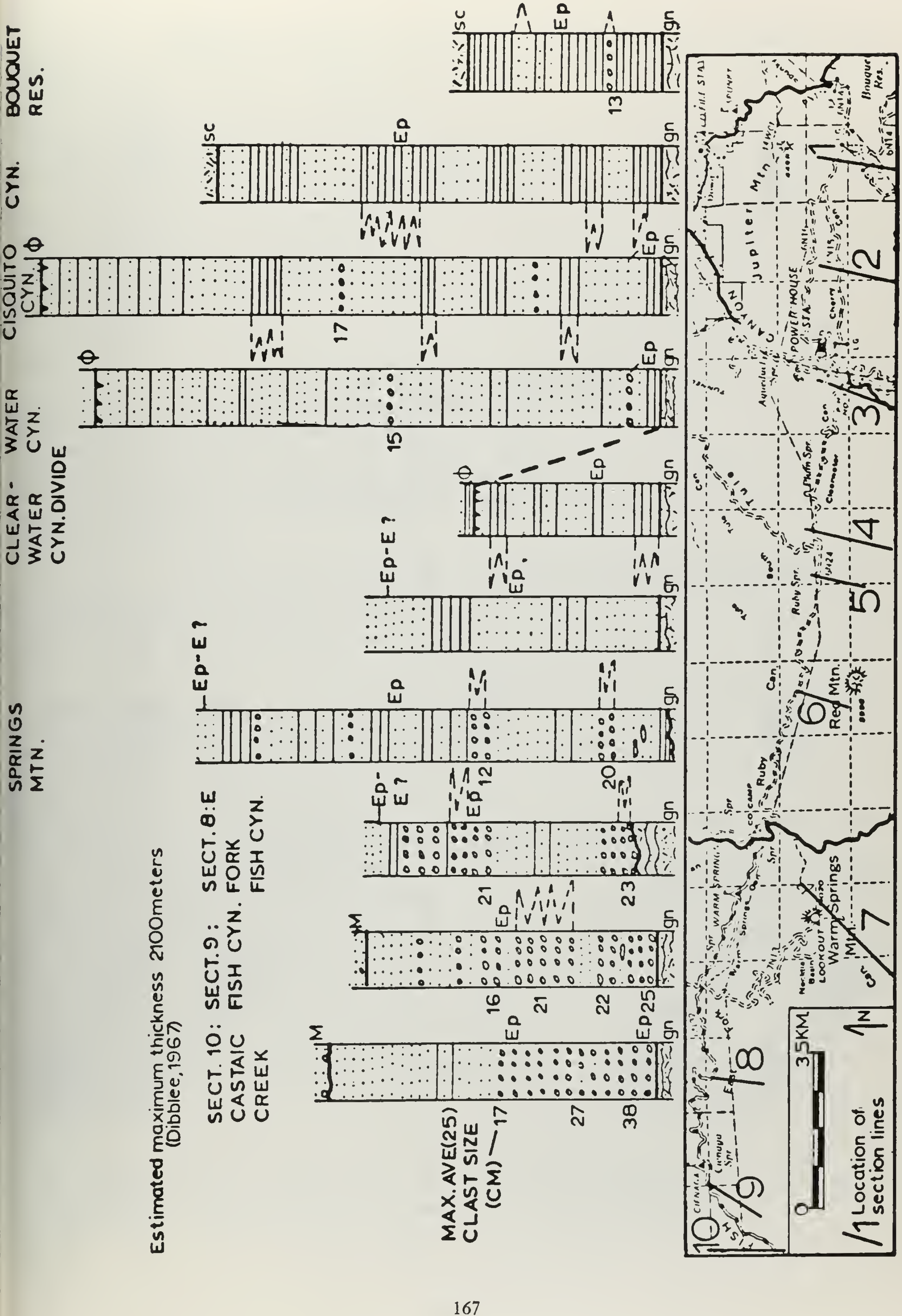

Figure 4. Stratigraphic sections and vicinity map San Francisquito Formation, Bouquet Reservoir to Fish Canyon.

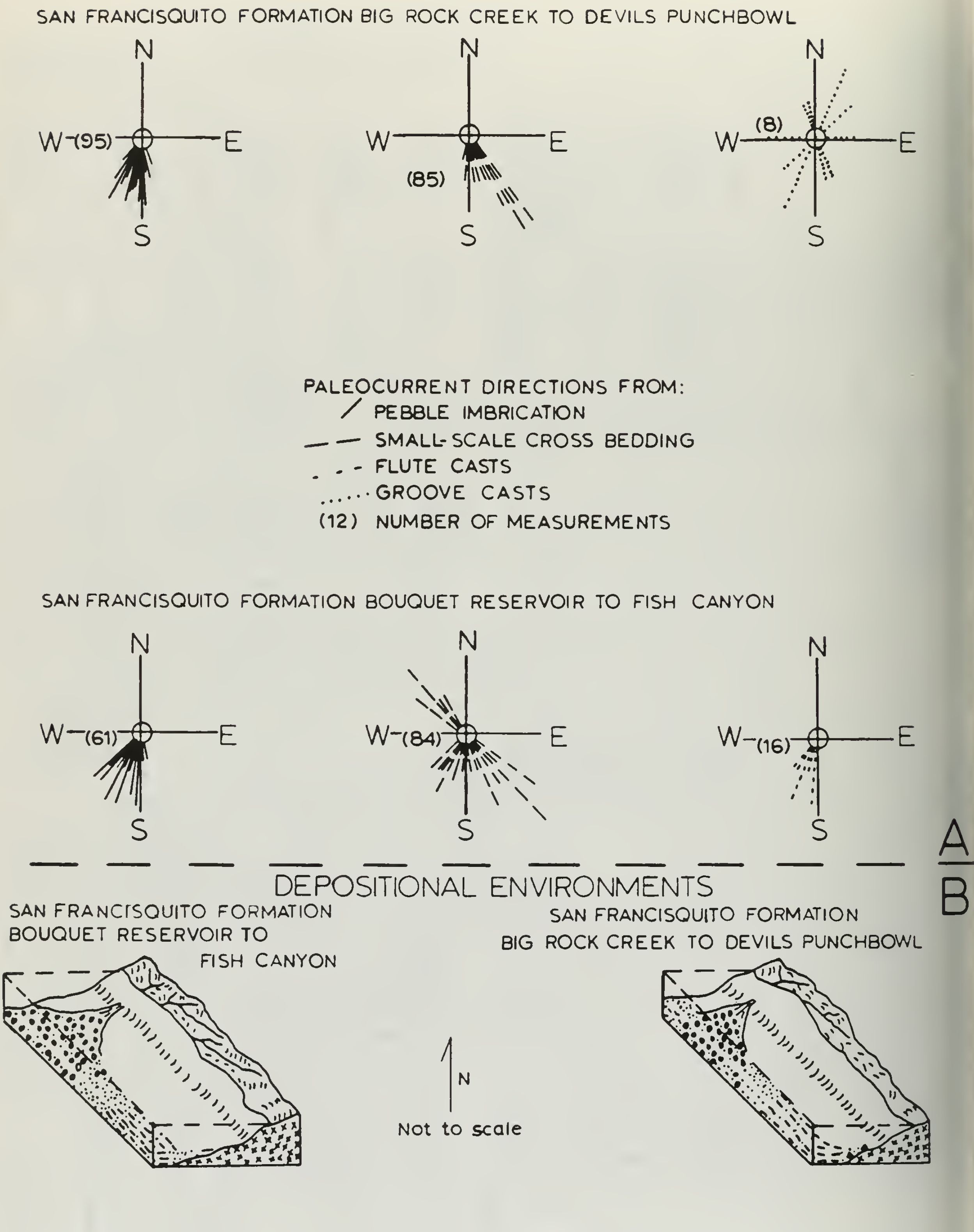

Figure 5. A - Paleocurrent directions, San Francisquito Formation,
B - Depositional Environments, San Francisquito Formation.

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SYNOPSIS OF THE GEOLOGY OF THE EASTERN SAN GABRIEL MOUNTAINS, SOUTHERN CALIFORNIA

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ABSTRACT

Eight major basement rock units are recognized and described on the basis of mapping about 350 km^2 of the eastern San Gabriel Mountains at 1:24,000. The basement rocks range in age from Precambrian(?) to Miocene. The metamorphic rocks can be assigned to the granulite, amphibolite, and greenschist facies. Quartz plutonites and cataclastic rocks are widespread.

Converging within the mountains are northwest-striking faults of the San Andreas system and east-striking faults of the Cucamonga fault zone. Between these fault complexes are a number of east- to northeast-striking faults, most of which converge with the San Jacinto fault zone to the northeast and the Cucamonga fault zone to the southwest. The San Jacinto fault appears to die out as it converges with the east- to northeast-striking faults. The Cucamonga fault is abruptly terminated on the east by faults related to the San Jacinto.

INTRODUCTION

The eastern San Gabriel Mountains present a bold south front that rises abruptly 2000 m above the alluvial fan-covered northern part of the upper Santa Ana Valley. The mountains are composed of a large variety of distinctive basement rocks with a predominantly east-striking structural grain. This rugged mountain front results from uplift on an east-striking fault zone termed the Cucamonga fault zone. The Cucamonga fault zone is the eastern part of a much longer fault complex that extends westward into the continental borderland. Within and bordering the mountains between the San Andreas system faults and those of the Cucamonga zone are several east-to northeast-striking faults (Figs. 1, 2).

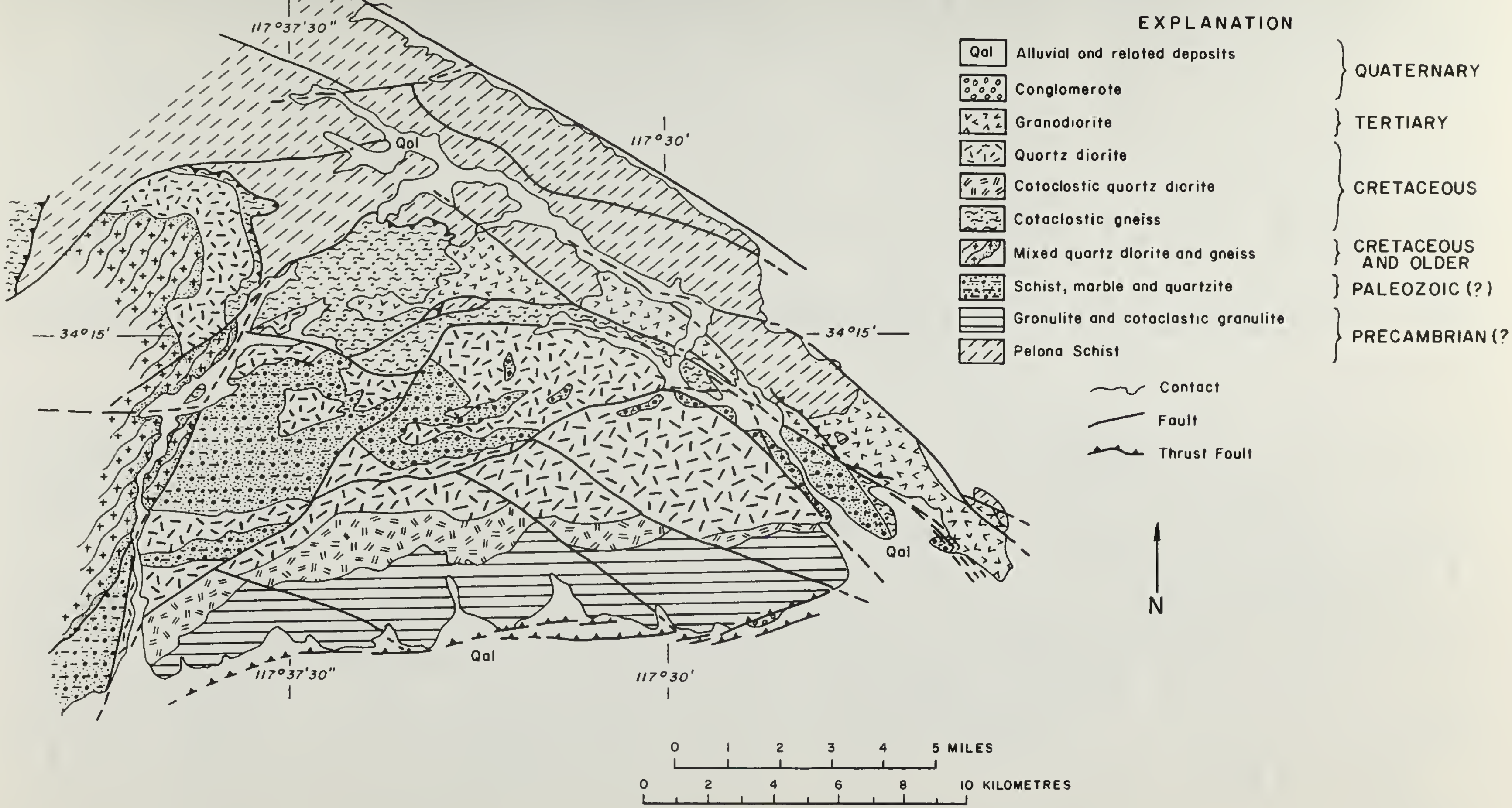
MAJOR ROCK TYPES

Granulitic rock, now largely cataclastically deformed, is exposed along the southern edge of the mountains. Considered to be Precambrian(?), it has been previously studied only in its western extent (Alf, 1948; Hsu, 1955). This unit consists of varied lithologie including layered gneiss, charnockitic rock, quartzite, marble, and amphibolit, which have undergone multiple penetrative deformations. The latest deformations, which were cataclastic, were most intense in the southern part of this unit, where it is also involved ir deformation related to movement within the Cucamonga fault zone.

Metasedimentary rock thought to be Paleozoic (Woodford, 1960), occurs nor of the granulitic rock and is separate from the latter by quartz diorite. Where it is best exposed on the east side of San Antonio Canyon, it is composed of thick sequences of amphibolit grade biotite schist, graphitic schist marble, and quartzite (Baird, 1956; Ehlig, 1958. These rocks are tightly folded with chiefly east-striking foliation and structural grain. Eastward from San Antonio Canyon they are complexly intruded by quartz diorite. Similar-appearing rocks are exposed in lower Lytle Creek, largely between the San Jacinto and Lytle Creek faults.

The Pelona Schist, which has been considered Precambrian(?) (e.g., Noble 1954; Dibblee, 1968) and Cretaceous(?) (Ehlig, 1968), is a greenschist-facies rock widely exposed on the northern flank of the mountains to the San

Fig. I GENERALIZED GEOLOGIC MAP OF THE EASTERN SAN GABRIEL MOUNTAINS SOUTHERN CALIFORNIA.



Andreas fault. Immediately beneath the Vincent thrust (Fig. 1) the schist consists of greenstone, which grades downward into predominantly gray albite-white mica-quartz schist. North of the Punchbowl fault the schist appears to be of slightly, but consistently, higher metamorphic grade than to the south. Although it appears structurally simple, the schist contains widespread and locally abundant slip folds and kink folds.

Cataclastically textured rock, dominantly cataclastic gneiss, overlies the Vincent thrust. Considered to be genetically related to movement on Vincent thrust (Ehlig, 1958), this rock varies considerably in thickness and may not be wholly a result of movement on the Vincent thrust. Adjacent to the Vincent thrust the cataclastic rock is very fine grained or aphanitic. Cataclastic rock occurs also on the east side of lower Lytle Creek.

Cretaceous quartz diorite and cataclastically deformed quartz diorite are widespread throughout the eastern San Gabriel Mountains south of the Vincent thrust. Mainly a medium- to coarse-grained biotite-hornblende quartz diorite, it is variable in texture and composition, especially in the vicinity of metamorphic rock units. Cataclastic textures are common and are pervasive in a zone along the southern part of its extent where it is a dark, flintlike rock studded with large porphyroblasts, or porpyroclasts, of hornblende and plagioclase; this cataclastic rock was termed the "black belt mylonite" by Alf (1948).

The foliated quartz diorite above the Vincent thrust near San Antonio Peak contains abundant inclusions of the distinctive Permian or Triassic Mount Lowe Granodiorite of Miller (1926).

West of San Antonio Canyon is a mixed assemblage of gneiss and quartz diorite, locally cut by basaltic dikes. North of the San Gabriel fault zone this unit contains masses of gneissic Mount Lowe Granodiorite.

Massive light-colored granodiorite of Miocene age (Hsu and others, 1963; Miller and Morton, 1974) is intrusive into cataclastic gneiss and the Pelona Schist. In its western extent, rock nea the intrusive margin is characterized by a hypabyssal texture; in eastern exposures all this rock consists of medium grained biotite granodiorite more representative of the body as a whole.

A small amount of conglomerate of Pliocene or Pleistocene age is exposed i the southeastern part of the mountains. In thrust contact with the granulite-cataclastic, this conglomerate completel lacks clasts of basement rock types now exposed in the eastern San Gabriel Mountains.

FAULTS

Thrusts of the east-striking Cucamonga fault zone and northwest-striking faults of the San Andreas fault system converge in the southeastern San Gabriel Mountains. The Cucamonga fault zone consists of numerous north-dipping imbricating thrusts along a 3-km-wide zone along the southern margin of the mountains. Many of the individual faults within this zone are marked by numerous scarps up to 35 m high in alluvial fans and exposures of granulite-cataclastic thrust over alluvial gravel (Morton and Yerkes, 1974).

The oldest and best known thrust in the San Gabriel Mountains, the Vincent thrust (Noble, 1954; Ehlig, 1958), is represented by four segments that are cut by high-angle faults. It is marked by a variety of cataclastic rock restin on the Pelona Schist. The cataclastic rock has been considered the product of deformation associated with the thrusting, probably during Late Cretaceous time (Ehlig, 1968). The Vincent thrust is intruded by the Miocene granodiorite

Fig. 2 GENERALIZED FAULT MAP OF THE EASTERN SAN GABRIEL MOUNTAINS, SOUTHERN CALIFORNIA.

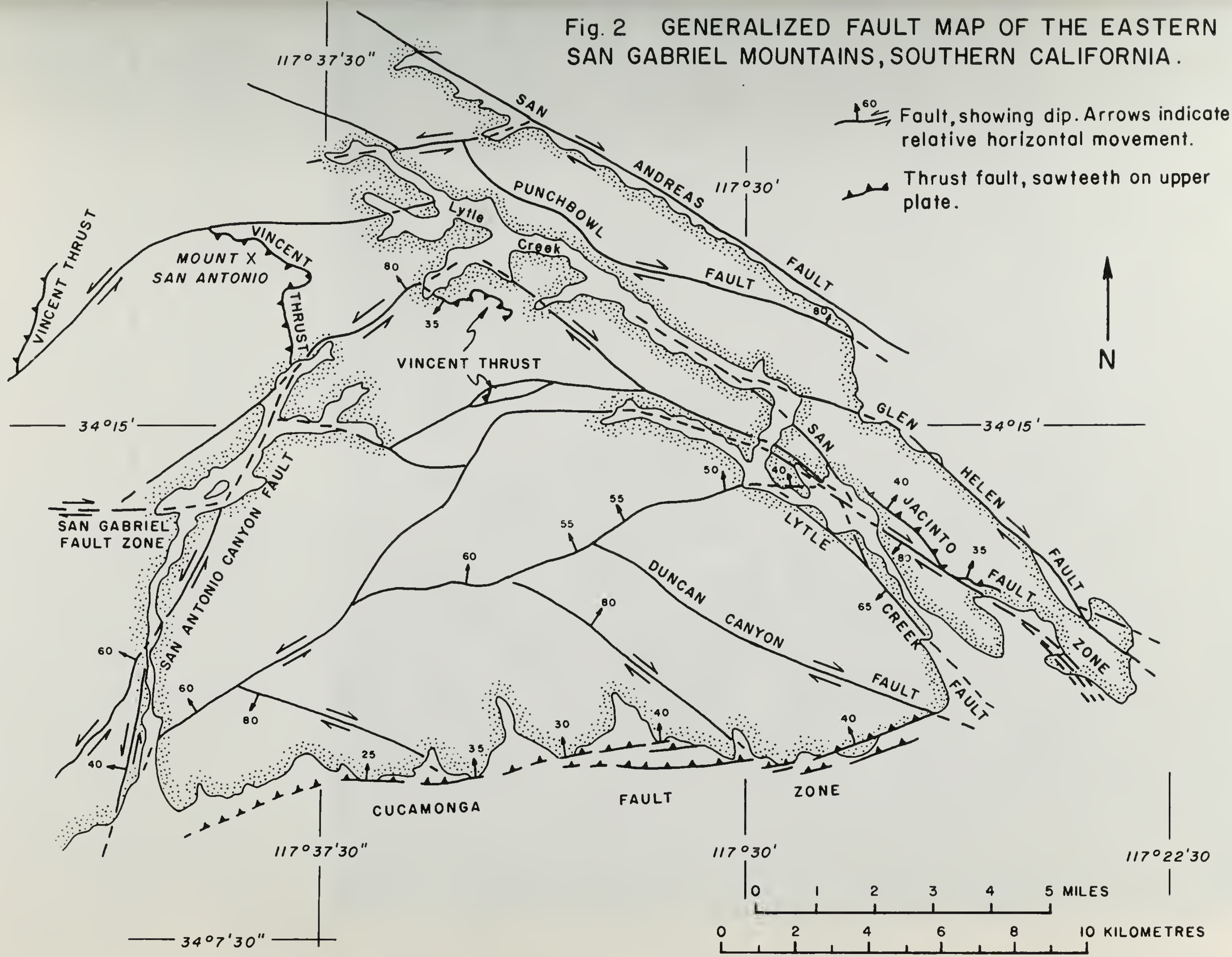


Figure 3. View looking northwest into the Lytle Creek drainage, eastern San Gabriel mountains. The San Jacinto fault zone enters the mountains in the center foreground occupying a fault line valley, before branching into the tributory canyons of Lytle Creek. Cucamonga Peak is the high point on the left and San Antonio Peak is the snow covered peak on the center skyline.

'he San Andreas system, physiographi-
ı y dominated by the San Andreas fault,
ı complex of subparallel faults along
within the northern part of the mount-
. Accented by numerous scarps and
ponds, the San Andreas fault zone
ns a series of linear fault-line
eys on the northern side of the
ntains. Oldest of the San Andreas
em faults in this area is the Punch-
fault (Noble, 1954), which apparent-
oins the San Andreas fault immediate-
ast of the San Gabriel Mountains
ton, unpub. mapping). Within the map
the Punchbowl follows a sinuous
se 1 to 2.5 km west of the San Andr-
and is marked by a nearly continu-
septum of sheared gneiss bounded by
Pelona Schist. The topographic ex-
sion of this fault is vague in most
es and totally lacks any feature sugg-
ve of recent displacement, except for
cal scarp in its eastern extent in
mountains. In the upper reaches of
le Creek, it is offset by a younger
heast-striking fault.

The San Jacinto fault zone consists of
ear zone up to 300 m wide where it
rs the San Gabriel Mountains. It
s any primary surface fault features
lies within a fault-line valley (Fig.
The youngest documented displace-
along this zone is thrusting of
ene granodiorite over Quaternary
ius derived from the granodiorite
ton, unpub. map). East of the San
into fault is the Glen Helen fault,
se surface expression includes scarps
sag ponds. The Glen Helen fault
rs westward 10 km within the mountains
join the San Jacinto fault in Lytle
ek.

West of the San Jacinto fault is the
le Creek fault which, like the San
into, displays no primary surface
lt features but does offset older
uvium.

Right-lateral separation of basement
k contacts on the combined San
Jacinto-Glen Helen faults is about 13 km. An additional 2 to 3 km right-lateral separation is recorded on three northwest-striking faults west of Lytle Creek. Thus, the aggregate observable lateral separation is about 10 km less than that documented by Sharp (1967) for the San Jacinto fault zone to the south.

Within the mountains the combined San Jacinto-Glen Helen-Lytle Creek faults form an imbricate complex, which progressively diverges westward into a series of east- to northeast-striking and north-dipping faults over a distance of 12 km (Fig. 3). Mapping in progress has revealed no geologic or surface expression of the San Jacinto fault 19 km within the mountains, a marked contrast from the 300-m-wide shear zone at the southern mountain front. As noted by Dibblee (1968) the San Jacinto fault joins neither the Punchbowl nor San Andreas fault. The trace offset of the Punchbowl fault is in uppermost Lytle Creek aligned with the projection of the San Jacinto fault, which probably explains earlier interpretations that the San Jacinto is a through-going fault.

The east- to northeast-striking faults, into which the San Jacinto merges or splays, show, where determinable, left-lateral separation of basement rock units and, with the exception of the Weber fault, reverse separation. Most of these faults converge near the mouth of San Antonio Canyon, seemingly merging with the Cucamonga fault zone, 26 km west of where the San Jacinto fault enters the mountains.

CONCLUSIONS

Current mapping in the eastern San Gabriel Mountains indicates that the surface trace of the San Jacinto fault does not join the San Andreas or Punchbowl faults but rather diverges into a series of east-to northeast-striking faults.

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BASEMENT ROCKS OF THE SAN GABRIEL MOUNTAINS, SOUTH OF THE SAN ANDREAS FAULT, SOUTHERN CALIFORNIA

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TRACT

\ highly varied basement terrane con-
ning unusual rock types is exposed
in the San Gabriel Mountains south of
San Andreas fault. Precambrian rocks
he western part of the range and
ining Soledad Basin include from
est to youngest: (1) amphibolite-
es gneiss and amphibolite; (2) dis-
ctive augen-gneiss derived from granite;
distinctive granulite-facies Mendenhall
ss formed from older granitic and
ssic rocks and subsequently largely
rograded to amphibolite-facies; and (4)
ly distinctive anorthosite, syenite and
bro. Permo-Triassic Lowe Granodiorite
s a large differentiated pluton within
northwestern and central parts of the
ge. It has four facies, each with a
racteristic mineralogy and texture.
above formations are intruded by Meso-
c and older(?) basic dikes which are
amorphosed to amphibolite. Late Meso-
c granitic rocks form extensive plutons
he central and southern parts of the
ge.

The above formations form the upper
te of the late Mesozoic-early Cenozoic
cent thrust fault; Mesozoic(?) Pelona
ist forms the lower plate. The Vincent
ust and Pelona Schist are exposed in
northeastern San Gabriel Mountains and
Sierra Pelona, and antiform north of
Soledad Basin. The thrust is marked
a thick zone of cataclastic rocks
atially retrograded to greenschist-facies.
Pelona Schist is derived from inter-
ded graywacke, siltstone, shale, basic
canics and minor chert and limestone
ch were prograded to greenschist-facies
chronously with the movement on the
cent thrust.

INTRODUCTION

The San Gabriel Mountains have been uplifted along the south side of the San Andreas fault in the central part of the Transverse Range Province. The range, predominantly composed of basement rocks, forms a rugged barrier between the subdued topography of the Mojave Desert to the north and the highly urbanized coastal lowland of the Los Angeles area to the south. To the east across Cajon Pass, an erosional gap along the San Andreas fault, lie the San Bernardino Mountains. The Santa Susana Mountains which are underlain by folded sedimentary rocks are a westward continuation of the San Gabriel Mountains. The northwestern part of the range merges into lower terrain of the Soledad Basin, due to a regional synformal structure and the presence of more easily eroded rocks in that area. Crystalline rocks exposed in the eastern part of the Soledad Basin and in Sierra Pelona, a small Transverse Range to the north, are a northwestward continuation of the basement terrane of the San Gabriel Mountains.

The San Gabriel Mountains and adjacent areas are readily accessible by paved road and road cuts provide many excellent exposures. No point is more than 5 miles from a paved road; however, rugged topography makes hiking off roads slow and tedious over much of the area.

Basement rocks exposed within this area range from Precambrian to Miocene in age and are described under the following headings: (1) Precambrian gneisses; (2) Precambrian anorthosite, syenite and related rocks; (3) Permo-Triassic Lowe Granodiorite; (4) pre-Cretaceous amphibolite and felsite dikes; (5) late Mesozoic granitic rocks; (6) Mesozoic Pelona Schist and associated Vincent thrust;

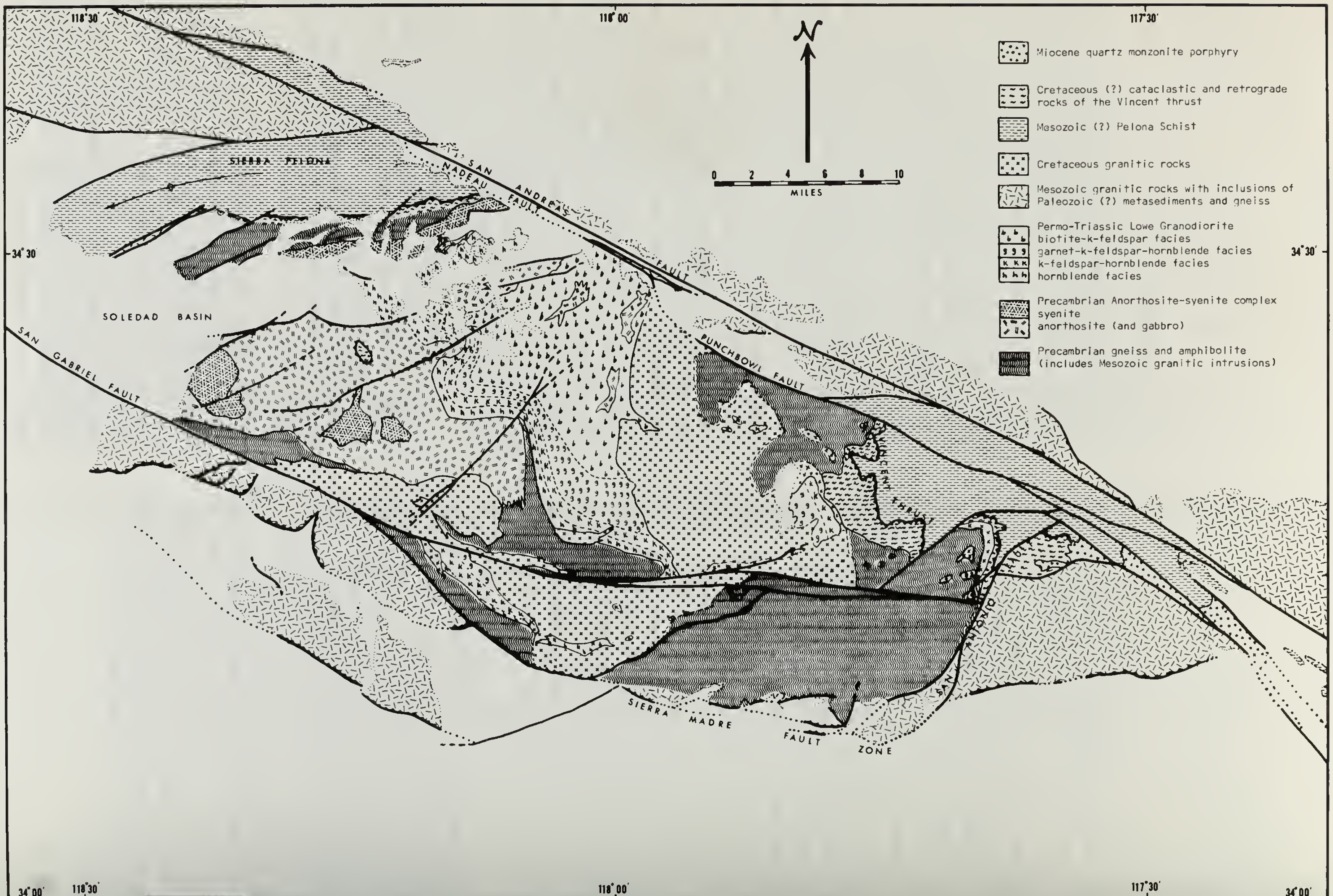

FIGURE 1. Map showing distribution of basement rocks in the San Gabriel Mountains. Modified after Geologic Map of California, Los Angeles Sheet (1969) and San Bernardino Sheet (1967). Distribution of syenite in part from Carter and Silver

Paleozoic(?) metasediments and related ss and migmatite; and (8) Miocene byssal intrusives. Rocks described er headings 1 through 5 form the upper e of the late Cretaceous(?) or early ozoic(?) Vincent thrust fault within main part of the area and the Pelona st forms the lower plate. Rocks ived from Paleozoic(?) strata are cribed out of sequence because they are gely of local occurrence. Cenozoic mentary rocks occur near the margins the San Gabriel Mountains but are not cribed here.

There is a conspicuous discontinuity in ement terrane across the San Andreas lt and the Nadeau-Punchbowl fault, which an inactive branch of the San Andreas ated a short distance south of the main lt. Quaternary uplift of the San riel Mountains, accomplished primarily reverse faulting along the southern gin and arching along the northern gin, is only indirectly related to the Andreas fault.

CAMBRIAN GNEISS

Gneisses of confirmed Precambrian age ur within the western San Gabriel ntains and adjoining Soledad Basin to north of the San Gabriel fault. The est consist of layered quartzofeld-thic gneiss and amphibolite metamor-sed to amphibolite facies and intruded augen gneiss. The augen gneiss is a tinctive rock containing abundant large vid of pink K-feldspar in a strongly iated matrix of biotite, oligoclase and rtz. It originated as a porphyritic nite about 1670 m.y. ago (Silver, 1971) was later metamorphosed. Similar augen iss is exposed near Frazier Park to the et of San Gabriel fault and in the tern Orocopia Mountains to the east of San Andreas fault. The Augen gneiss fall three areas yield the same age Silver, 1971). The augen gneiss of this ra can be seen along Sierra Highway in t Canyon north of Davenport Rd.

The Mendenhall Gneiss, described and ed by Oakeshott (1958), p. 21-29), occurs in the western San Gabriel Mountains to the south and southeast of the anorthosite-syenite complex and can be seen in Pacoima Canyon to the north of Little Tujunga Rd. It appears to be an extension of the terrane described above but it underwent granulite-facies metamorphism about 1440 m.y. ago (Silver and others, 1963). Subsequent amphibolite-facies metamorphism has largely destroyed the granulite-facies mineral assemblages but has left distinctive replacement textures. Relict hypersthene, augite, garnet and alkali feldspar (hairline perthite to antiperthite) have survived locally. Blue to violet quartz is a more widespread relict. Offset equivalents to the Mendenhall Gneiss occur west of the San Gabriel fault in the area south of Frazier Park (Crowell, this vol.) and east of the San Andreas fault in the Orocopia Mountains (Crowell, this vol.).

Gneiss and amphibolite of probable Precambrian age are widespread in the central San Gabriel Mountains but have not been dated. They are profusely intruded and locally migmatized by younger granitic rocks. Some have conspicuous compositional banding suggestive of a sedimentary origin; others are fairly homogeneous suggesting an igneous origin. All have a simple amphibolite-facies mineralogy consisting mainly of feldspar, quartz, biotite and hornblende.

PRECAMBRIAN ANORTHOSITE, SYENITE AND RELATED ROCKS

These rocks form a large massif in the western San Gabriel Mountains and eastern Soledad Basin recently described by Carter and Silver (1972) and previously described by Miller (1931, 1934), Oakeshott (1937, 1954, 1958), Higgs (1945), and Crowell and Walker (1962). The complex was emplaced 1220 m.y. ago (Silver and others, 1963; Silver, 1971). The most abundant rock type is purplish-gray to blue-gray and white andesine anorthosite. It occurs in association with norite in what was initially a stratiform body with prominant compositional layering produced by gravitational settling of crystals (Carter and Silver, 1972). Subsequent folding, faulting and intrusion by granitic rocks has complicated the structure. Excellent exposures are present along Angeles Forest Highway south of Baughman Spring.

Alkali syenite is exposed in the southwestern part of the anorthosite body and in a belt, 1 to 3 miles wide, extending along the northern edge of the Soledad Basin from Agua Dulce Canyon to the San Andreas fault, a distance of 12 miles. The syenite consists mainly of alkali feldspar which has exsolved into a distinctive hairline mesoperthite. Blue to violet quartz is a minor constituent in many places and is sufficiently abundant locally to refer to the rock as an alkali granite. Pyroxene and olivine were originally present in most of the syenite but are replaced by aggregates of tiny biotite crystals. In spite of its dark drab appearance, the syenite is a highly distinctive rock and provides strong evidence for offset along the San Andreas fault. Identical syenite is one of the main rock types within the anorthosite complex of the Orocopia Mountains described by Crowell and Walker (1962) and Crowell (this vol.). Syenite clasts also occur in alluvium offset along the San Andreas fault. The syenite is well exposed on Tenhi Mountain south of Lake Palmdale.

In addition to occurrences within the main anorthosite body, metamorphosed gabbro, pyroxenite and peridotite occur as pendants in Lowe granodiorite and Mesozoic granitic rocks in the northern and central San Gabriel Mountains.

PERMO-TRIASSIC LOWE GRANODIORITE

The Lowe Granodiorite is about 220 m.y. old (Silver, 1971). This is a unique age among plutonic rocks in southern California. It is a distinctive rock which is exposed over an area of 100 square miles in the central and northwestern San Gabriel Mountains and eastern Soledad Basin. All exposures appear to belong to a single northwest-trending pluton. The pluton's western margin forms a sharp smooth steeply inclined contact against Mende hall Gneiss and the anorthosite-syeni complex. No Lowe Granodiorite is know to crop out west of this margin. The eastern part of the pluton is disrupte by a large Cretaceous granitic intrusi but septa of Lowe Granodiorite occur within migmatite and gneiss further ea indicating that the eastern margin was irregular with apophyses extending con siderable distances into the country r The northern part of the pluton is tru cated by the San Andreas fault. The southern part is offset 14 miles to th right along the north branch of the Sa Gabriel fault. The southern part is disrupted by younger granitic intrusi but pendants of the marginal facies in dicate the pluton did not extend as fa south as the present range margin or t south branch of the San Gabriel fault

The Lowe Granodiorite has an origi foliation and compositional zoning sub parallel to the pluton's western marg In most areas a late Mesozoic regiona metamorphism has enhanced the origina foliation and has modified igneous te tures through granulation and partial recrystallization. The Lowe Granodio is characterized by a high feldspar co tent, ranging from about 60 to 95 perc and a low quartz content, generally varying on either side of 10 percent. Its name is misleading in that it var from diorite near the pluton's margin granite and syenite in the interior. Four facies have been distinguished f mapping purposes as shown in Fig. 1. Along the border is the hornblende fa composed of abundant rectangular to o black hornblende phenocrysts set in a matrix of white andesine and minor i stitial quartz and K-feldspar. In ma areas the hornblende has been extensi altered to green epidote. The hornbl facies grades into the hornblende-K-f spar facies with the fairly abrupt appearance of abundant K-feldspar phe crysts scattered through the matrix o calcic oligoclase to sodic andesine a minor quartz. The hornblende phenocr are larger and less abundant than in ıler facies and, where particularly ɛse grained, create a strikingly spotted ɛmatian" textured rock. The next zone ıarked by the incoming of garnet and is ɜrred to as the hornblende-K-feldspar-ıet facies. The garnets occur both as ṣeminated crystals, as much as 2 cm ɒss, and in concentrations along seams ɛe late crystallizing fluids migrated. ɜldspar phenocrysts in this facies ɑlly attain a length of 10 cm. The ɜrior facies contains a small amount of ɛite, typically less than 10 percent, ɑg with feldspar. In this facies K-ɪdspar occurs as large phenocrysts within ɑ of the area but in places it occurs ɛread as part of the white granular ɪix. Plagioclase, the most abundant ɛral, ranges from oligoclase to albite. ɪtz tends to occur in veinlets and ɛure interstitial grains. Its abun-ɪce varies from a trace to about 25 ɛent in an area of quartz-rich rock near ɪle Rock Creek. The biotite-bearing ɔks crystallized last and may have ɔned by a resurgence of magma from ɪth. In Soledad Pass the biotite-bear-ɪ facies is in contact with the horn-ɪde border facies. Elsewhere tongues ɪornblende-bearing rocks interfinger ɪ biotite-bearing rocks but biotite and ɔblende do not coexist in the same ɜr. All of the facies of Lowe Grano-ɪite can be seen along Angeles Forest ɪway north of the anorthosite complex.

Lowe Granodiorite occurs east of the ɑ Andreas fault in a few small outcrops ɪcovered by Crowell (1973) at the north ɪ of the Chocolate Mountains and as ɔphyses in gneiss in the central Choco-ɜ Mountains recently discovered by John ɪlon. Clasts of all four facies of the ɔɜ Granodiorite occur in a mudflow ɛccia overlying lava flows in the Oligo-ɜɜ-lower Miocene Diligencia Formation at ɑyon Springs in the Orocopia Mountains. ɪ clasts have been dated by Silver (1971) ɪ confirms their unique age of 220 m.y. ɪng the north side of the San Gabriel ontains Pleistocene alluvial deposits ɔtaining abundant Lowe Granodiorite ɪsts are offset along the San Andreas ɑlt as much as 20 miles from their probable source area. The distribution of Lowe Granodiorite clasts also provides supportive evidence for right-slip along the San Gabriel fault (Ehlig, 1973; Crowell, this vol.; Ehlig and others, this vol.).

PRE-CRETACEOUS AMPHIBOLITE AND FELSITE DIKES

Metamorphosed dikes are common in areas underlain by the rocks described above but are cut by Cretaceous granitic rocks. The dikes are typically only a few feet thick and have straight parallel walls. The original dikes were mainly andesite and basalt but have been metamorphosed to amphibolite consisting of hornblende and plagioclase with a metamorphic texture. Biotite is abundant in some dikes. Metamorphosed rhyolite dikes containing scattered phenocrysts of quartz in a granophyric groundmass occur in a north-south belt extending across the west-central part of the San Gabriel Mountains. Some metarhyolite dikes form subhorizontal sheets, as much as 50 feet thick, which are traceable over an area of more than a square mile.

The dikes are another feature characteristic of the pre-Cretaceous basement terrane and show that some areas have experienced little internal deformation since dike emplacement.

LATE MESOZOIC GRANITIC ROCKS

Common types of medium-grained granitic rocks, typically ranging from melanocratic hornblende quartz diorite to leucocratic biotite quartz monzonite intrude all other pre-Cenozoic basement rocks except Pelona Schist. One intrusion along the south side of the anorthosite complex has been dated at about 80 m.y. (Carter and Silver, 1971). An intrusion into Paleozoic(?) metasedimentary rocks east of the San Antonio fault has been dated at about 105 million years (Hsu and others, 1963) but its relationship to rocks west of the fault is uncertain. The largest pluton, which is exposed over an area of 75 square miles in the central part of the range, has not been dated.

Contacts between granitic rocks and their hosts tend to be sharp in the area of sparse intrusions in the northwestern part of the range but extensive migmatization has also occurred in areas of Paleozoic(?) metasedimentary rocks described below.

MESOZOIC(?) PELONA SCHIST AND ASSOCIATED VINCENT THRUST

In the northeastern San Gabriel Mountains erosion has cut through the previously described rocks and exposed the Vincent thrust fault and about 10,000 feet of underlying Pelona Schist (see fig. 1). The Vincent thrust is marked by a thick zone of cataclastic and retrograde metamorphic rocks developed from the basal part of the upper plate. The fault contact between Pelona Schist and the overlying rocks can be placed within an inch where exposures are perfect but the actual fault movement was distributed throughout the zone of cataclastic and retrograde metamorphic rocks overlying the schist and to a lesser extent within the Pelona Schist as well.

The Pelona Schist has undergone prograde metamorphism within the lower greenschist-facies and is characterized by highly developed schistosity parallel to bedding. The most abundant lithology is gray muscovite-albite-quartz schist derived from thinly interbedded graywacke, siltstone and shale. The gray color is due to finely disseminated graphite. Albite porphyroblasts in the coarser-grained schists are colored gray to black by graphite. Green chlorite-actinolite-epidote-albite schist derived from basaltic tuff is common in the upper part of the sequence. Quartzite derived from chert and thin beds of marble are minor rock types typically interbedded with green schist. Prograde metamorphism of the schist occurred synchronously with movement along the Vincent thrust, probably as the combined result of deep burials beneath the thrust's upper plate, heat derived from the upper plate and dynamic forces caused by the thrusting (Ehlig, 1958, 1968).

The zone of cataclastic rocks along the Vincent thrust varies from about 2 to over 2000 feet thick and includes mylonite, protomylonite, ultramylonite mildly cataclastic tectonic inclusions and, near the base of the thrust, rock at various stages of retrograde metamo phism to greenschist-facies mineral assemblages. The variation in thickne of thrust rocks is due to tectonic thickening and thinning and involves extensive folding. A large overturned fold in the Pelona Schist directly beneath the thrust indicates that here t upper plate moved from the southwest during a late stage in the movement. displacement along the thrust has not been determined but is likely to be several tens of miles.

The Vincent thrust apparently exten beneath the entire San Gabriel Range a reappears along the southeastern edge Sierra Pelona, a tight antiform exposi Pelona Schist to the north of the synformal Soledad Basin. Relationships a Sierra Pelona are similar to those in San Gabriel Mountains except that the prograde metamorphism of the schist reaches lower amphibolite-facies close the thrust and the tight post-metamorp antiformal folding has caused the more flexible schist to pierce upward throu the overlying cataclastic and upper pl rocks along much of its contact.

The Pelona Schist forming Blue Ridg between the Punchbowl and San Andreas faults in the northeastern San Gabriel Mountains appears to be displaced from Sierra Pelona by 25-30 miles of right slip along the Punchbowl fault as described below. The Pelona Schist and Vincent thrust rocks are also exposed low hills around San Bernardino and Redlands and further east in the San Berr dino Mountains to the south of the Sar Andreas fault. This occurrence is an eastward continuation of those exposec the eastern San Gabriel Mountains to le south of the Punchbowl fault (see Dibbe this vol.). The Orocopia Schist and ociated Orocopia thrust in southeastern ifornia are probably an eastward con- uation of the Pelona Schist and Vincent ust that are offset along the San reas fault (see Crowell, this vol.).

The depositional age of the Pelona ist has not been determined but need be older than late Cretaceous. Meta- phism of the schist and associated elopment of the Vincent thrust fault urred after Cretaceous granitic rocks e intruded into the thrust's upper te. A metamorphic age of about 52 m.y. obtained by K-Ar and Rb-Sr methods lig and others, 1975). Although this represent a post-metamorphic cooling , it suggests the schist was hot as ently as Eocene and was therefore ply buried.

EOZOIC(?) METASEDIMENTS AND RELATED ISS AND MIGMATITE

These rocks occur (1) to the north of San Andreas fault, (2) east of the San onio fault in the eastern San Gabriel ntains, (3) south of the San Gabriel lt in the southwestern San Gabriel ntains and adjoining Verdugo Mountains, (4) in a small area west of San Gabriel yon near the south-central range mar- . The exposures north of the San reas fault consist of marble and calc- icate rocks emersed in quartzofeld- pthic gneiss, migmatite and granitic oks. Amphibolite-facies metamorphism curred during emplacement of granitic oks. Similar rocks are exposed in the etern San Bernardino Mountains to the oth of the San Andreas fault.

Metasedimentary rocks constitute a inificant part of the terrane east of h San Antonio fault. Strata derived m quartz arenite, dolomite, siltstone n aluminous and carbonaceous shale have umulative thickness of more than 5000 et. High temperature amphibolite-facies eamorphism occurred during intrusion of nitic rocks. In the southern part of h area, a belt of mylonitic rocks eeral thousand feet thick trends nearly at-west from the San Antonio fault to the eastern edge of the range (Alf, 1948; Hsu, 1955). Part of the rocks south of this belt have undergone granulite facies metamorphism. The mylonite formed after emplacement of Cretaceous granitic rocks. The eastward and westward extensions of this mylonite belt have not been located. The westward extension is probably con- cealed beneath the sedimentary cover in the San Gabriel Valley. Perhaps the belt is associated in some way with the Vincent thrust or a belt of mylonite along the east side of the San Jacinto Mountains.

Metasedimentary rocks south of the San Gabriel fault in the western part of the range and adjoining Verdugo Mountains include the same lithologies as those east of the San Antonio fault but are less well preserved. Metamorphism was in the upper amphibolite-facies and produced extensive migmatitic gneiss along the south-central range margin.

The Paleozoic(?) metasedimentary rocks appear to be too fragmentary and too wide- spread to be useful at present in establishing offset along the San Andreas fault.

MIOCENE HYPABYSSAL INTRUSIVES

Stocks of biotite quartz monzonite porphyry and associated dikes and sills intrude Pelona Schist and overlying rocks in the upper plate of the Vincent thrust in the eastern part of the range. Several K-Ar and Rb-Sr age determinations suggest an age of 15 to 20 m.y. (Hsu and others, 1963; Miller, 1974). Intrusions are truncated by the Punchbowl fault and do not occur in Pelona Schist of Blue Ridge but are present in Pelona Schist and overlying rocks in the area around San Bernardino and Redlands.

Shallow intrusive dikes are locally common in the southern and east-central San Gabriel Mountains. The most abundant are andesite, diabase and dacite but olivine basalt and quartz latite also occur. The dikes are generally assumed to be lower to middle Miocene in age because of the occurrence of extrusive volcanic rocks of that age in the surrounding region.

SAN ANDREAS AND NADEAU-PUNCHBOWL FAULTS

Along the northern edge of the San Gabriel Mountains the San Andreas fault system includes the presently active San Andreas fault and the Nadeau-Punchbowl fault, located one to two miles south. The slice between the two faults is largely intact though strongly deformed. The Nadeau-Punchbowl fault is an old abandoned strand of the San Andreas fault showing no evidence of Holocene activity. It has a right slip of about 25-30 miles (Dibblee, 1967, p. 114; Ehlig, 1968, p. 301). This is based in part on (1) correlation of Fenner fault, which separates Pelona Schist from Paleocene marine strata and underlying granitic and gneissic rocks north of the Punchbowl fault, with the San Francisquito fault along the north side of Sierra Pelona and (2) similarities between Pelona Schist of Blue Ridge and Sierra Pelona.

Basement terrane north of the San Andreas fault in the vicinity of the San Gabriel Mountains consists mainly of common types of granitic rock and is devoid of distinctive rock types found south of the fault. However, all of the distinctive formations, including augen gneiss, Mendenhall gneiss, anorthosite, syenite and Lowe Granodiorite, occur across the fault in the Orocopia and Chocolate Mountains (Crowell, this vol.). This, in combination with data presented elsewhere in this volume, constitutes compelling evidence for about 150 miles of right slip along the San Andreas fault, including displacement along the Nadeau-Punchbowl fault.

Offset stream gravels provide abundant evidence for Quaternary offset along the north side of the San Gabriel Mountains. Streams draining northward from the mountains have deposited fans across the fault. Nearly every major stream has a different assemblage of rock types within its drainage area. In Cajon pass, the lower part of the Pleistocene Shoemaker Gravel contains clasts of Lowe Granodiorite and other rock types derived from 20-25 miles to the west. Offsets of as much as 10 miles late Pleistocene alluvium are particularly convincing because the drainage systems which provided the alluvium are still intact.

SAN GABRIEL FAULT

The San Gabriel fault is an inactive strand of the San Andreas fault with a net right slip of 35-40 miles (Crowell this vol.; Ehlig and others, this vol.). The fault splits into two branches with the western San Gabriel Mountains. The north branch offsets the Lowe Granodiorite-Mendenhall Gneiss contact about 1 miles. The north branch is truncated by the San Antonio fault in the eastern part of the range. The south branch extends to the south-central range margin where it becomes enmeshed with younger reverse faults of the Sierra Madre fault zone. This creates uncertainty regarding the location of the south branch east of its juncture with the Sierra Madre fault.

QUATERNARY RANGE UPLIFT

The San Gabriel Mountains have acquired their present elevation largely as the result of Quaternary displacement on northward dipping reverse faults of the Sierra Madre fault zone along the south margin of the range. The reverse faults are locally controlled by preexisting zones of weakness, such as older faults and foliation. However, the comparatively simple gross structure of the Sierra Madre fault zone is superimposed upon a complex preexisting structure and appears to be unrelated to the geologic evolution of basement rocks exposed within the range.

Uplift has also resulted from arching as shown by northward dips of as much as 30 degrees in lower Pleistocene alluvial deposits along the northeastern margin of the range. The San Andreas fault extends across the northeastern part of the range but shows little evidence of direct participation in range uplift. For example, mountainous terrain is present on both sides of the San Andreas fault in the E

ı-Wrightwood area with no evidence of
ferential vertical displacement along
fault.

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LATE TERTIARY NONMARINE ROCKS, DEVIL'S PUNCHBOWL AND CAJON VALLEY, SOUTHERN CALIFORNIA

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TRACT

The Devil's Punchbowl, the type loc-
ty of the Tertiary Punchbowl Formation,
located near Valyermo, California, and
urs on the southwest side of the San
reas Fault. Exposures of similar
ks in Cajon Valley, located about 33
(20 miles) to the southeast, occur on
northeast side of the fault and pre-
us workers have suggested that these
osures indicate about 33 km of right-
eral slip on the San Andreas Fault.

The two rock units differ in age and
not correlative. Both were deposited
streams flowing from the northeast or
t. Both contain locally derived, main-
'granitic" clastic debris, but vol-
ic and metavolcanic cobbles found in
of two terranes may have had a more
tant source on the Mojave Desert.
"Sidewinder Volcanic Series" near
torville may have been the source of
metavolcanic rocks in the Cajon
ley succession, but the source of the
il's Punchbowl volcanic clasts is more
cure. It is unlikely that the Devil's
chbowl was aligned with Cajon Valley
ing the times when either of their
chbowl sediments were being deposited.
ther the two areas were aligned at
er times during the Tertiary involves
nsideration of the amount and timing
right-lateral slip on the San Andreas
lt.

RODUCTION

Noble (1953, 1954a) described the
logy and stratigraphy in the Pearland
Valyermo quadrangles, Southern
ifornia (Fig. 1). One of the import-
Cenozoic stratigraphic units was des-
ated as the Punchbowl Formation, the
e exposures of which are displayed in
spectacular Devil's Punchbowl found in the Los Angeles County Park located southwest of Valyermo. In the Pearland Quadrangle, Punchbowl rocks occur southwest of the San Andreas Fault; in the Valyermo area, they occur both northeast and southwest of the fault, according to Noble (1953, 1954a). Because some or all of the Punchbowl rocks in the Pearland area and those north of the San Andreas in the Valyermo area appear to be of different lithologic composition, provenance and, probably, age than the sediments in the type area (Woodburne, 1975a and b), only the type Punchbowl Formation is considered in the present report (see also the article by Allan Barrows in this volume).

Additionally, Noble (1954b) correlated the type Punchbowl Formation with sediments of generally similar character in Cajon Valley (Fig. 1), located about 33 km (20 miles) to the southeast of the Devil's Punchbowl. The Cajon Valley rocks were studied further by Woodburne and Golz (1972). In contrast to the sediments in the type area, the Cajon Valley rocks occur on the northeast side of the San Andreas, and various workers have cited these now disjunct outcrop areas as evidence for about 33 km of post-depositional right-lateral slip on the San Andreas Fault. Woodburne and Golz (1972) indicate that the two Punchbowl units differ in stratigraphic detail and age so that they do not directly record the amount of separation on

Figure 1. Generalized geologic map of western Transverse Ranges, from Cajon Pass to Soledad Pass. At this scale, the Vaqueros (?) Formation occurs in a minute outcrop in the southern third of Cajon Valley. After Woodburne and Golz (1972).

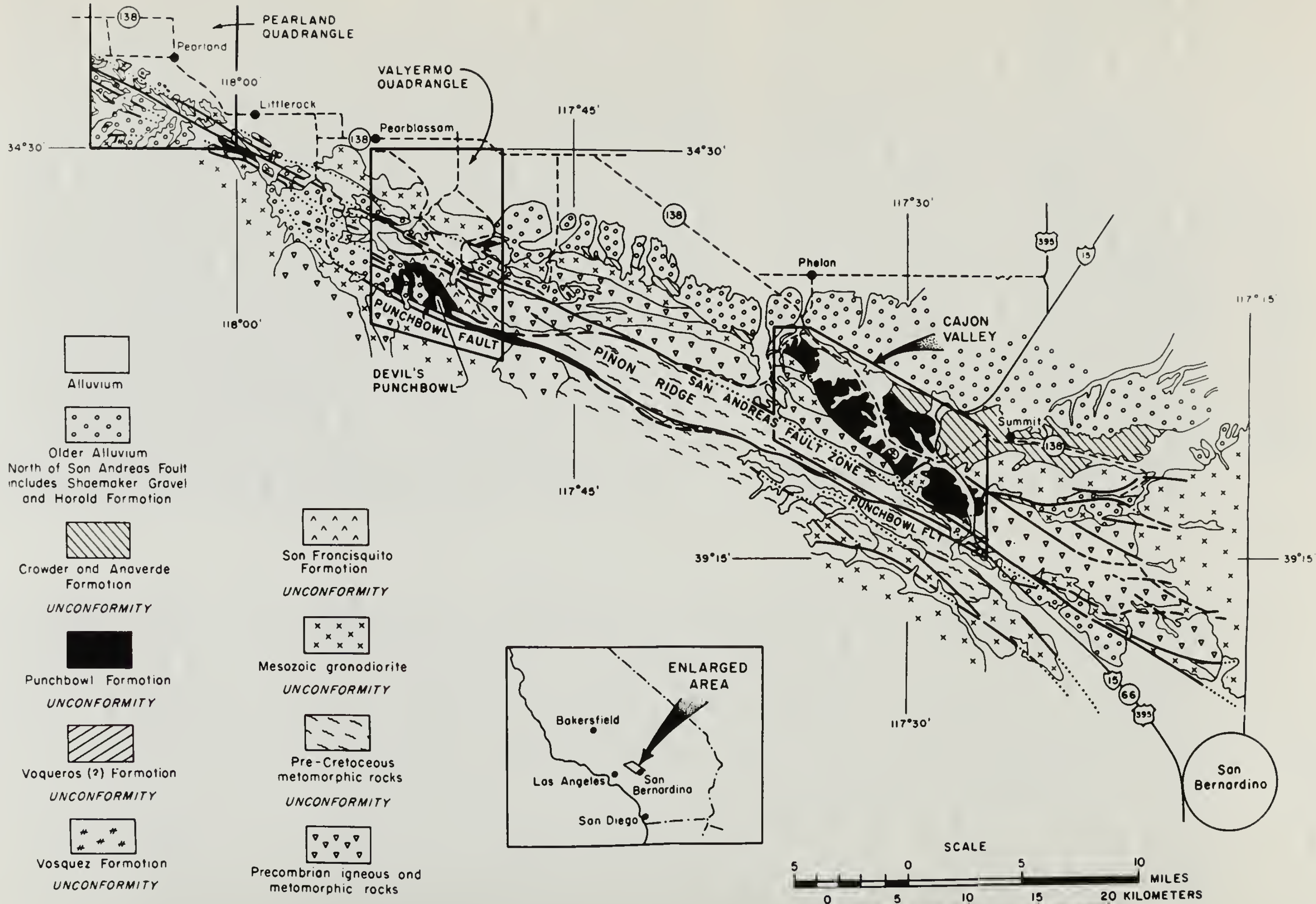

PEARLAND
QUADRANGLE
Pearland
138
118°00'
Littlerock
VALYERMO
QUADRANGLE
Pearblossom
34°30'
117°45'
118°00'
PUNCHBOWL FAULT
DEVIL'S
PUNCHBOWL
PIÑON RIDGE
SAN ANDREAS FAULT ZONE
PUNCHBOWL FLT
117°30'
Phelon
395
15
CAJON
VALLEY
Summit
117°15'
39°15'
66
San
Bernardino
Alluvium
Older Alluvium
North of San Andreas Fault
includes Shoemaker Gravel
and Harold Formation
Crowder and Anaverde
Formation
UNCONFORMITY
Punchbowl Formation
UNCONFORMITY
Voqueros (?) Formation
UNCONFORMITY
Vosquez Formation
UNCONFORMITY
San Francisquito
Formation
UNCONFORMITY
Mesozoic granodiorite
UNCONFORMITY
Pre-Cretaceous
metamorphic rocks
UNCONFORMITY
Precambrian igneous and
metamorphic rocks
ENLARGED
AREA
Bakersfield
Los Angeles
San
Bernardino
San Diego
SCALE
5 0 5 10
MILES
0 5 10 15 20 KILOMETERS

Fig.1

h fault. Resolution of this question nolves further considerations such as h tectonic-depositional histories of h two areas and their respective paleo-egraphic development. This paper sets u some of the stratigraphic and other tributes of the Punchbowl Formation in h Devil's Punchbowl and Cajon Valley n comments on possible interrelation-hps of the two areas.

EIL'S PUNCHBOWL

eeral Statement

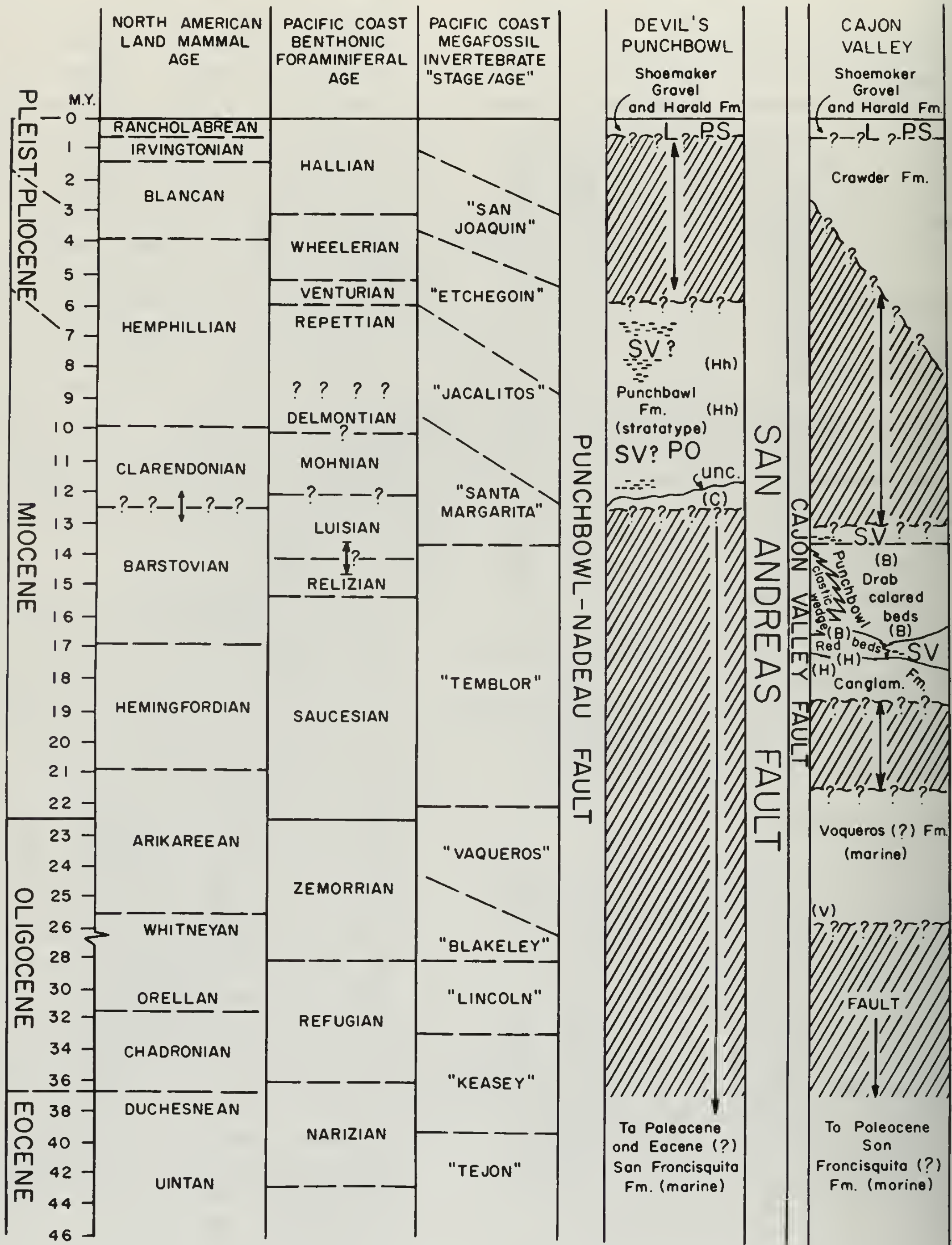
The type Punchbowl Formation is a ucession of nonmarine, generally coarse-rined sediments that unconformably over-is Paleocene marine strata (San Fran-iquito Formation) and are unconforma-l overlain by beds of Pleistocene age Hrold Formation: Noble, 1954a). The uchbowl deposits, about 4,000 feet hck, are folded into an asymmetric west-lnging syncline. This syncline is hrply truncated on the southwest by the uchbowl Fault (Fig. 1), marked by a hck, conspicuous, white gouge zone.

tatigraphy and Age

Noble (1954a) divided the type Punch-cl Formation into two members. The cer member, about 330 m (1,000 ft.) hck, is composed mainly of white to iht buff arkosic conglomerate and cglomeratic sandstone, with a few beds ffine-grained sandstone. Some of the cglomerate beds are very coarse-grained, ih subangular to subrounded pebbles, cbles, and boulders up to 2 feet in imeter. Most of these larger clasts r quartz diorite gneiss and granod-cite, possibly derived from pre-etiary basement rocks in Piñon Ridge, cated about one mile east of the ycline. Noble (1954a) suggested that hse Punchbowl clasts were similar cbasement rocks found southeast of h Punchbowl Fault, but Pelka (1971) a indicated that the formation was de-cited in a westerly direction rather than from the south. As such, the gran-odiorite and quartz diorite gneiss found in Piñon Ridge is a likely source for the Punchbowl clasts. Other, less abundant, clasts are cobbles of sandstone reworked from the underlying San Francisquito Formation, and boulders of "polka-dot" cordierite granite with no presently known source (Pelka, 1971). Some of the cobbles of the lower member are clasts of "meta" latite and quartz latite ash-flow tuff, apparently reworked from the San Francisquito Formation, that resemble rocks present in the "Sidewinder Vol-canic Series," north of Victorville (written commun., 1974, Katherine J. Barrows, Department of Geology, Univ. of Calif., Los Angeles, and Allan G. Barrows, California Division of Mines and Geology, Los Angeles).

At the very base of the Punchbowl succession, and separated from overlying rocks by an unconformity according to Noble (1954a), is a reddish-purple sand-stone unit that contains great amounts of material derived from the underlying San Francisquito Formation. Noble (1954a) nevertheless included this basal unit in the Punchbowl Formation and remains of a fossil horse, Pliohippus cf. P. tehonensis have been recovered from the sedi-ments. On this basis, the base of the type Punchbowl Formation has been assign-ed Clarendonian age (Tedford and Downs, 1965; Woodburne and Golz, 1972). Other fossils, taken about 330 m (1,000 ft.) above the base of the formation, occur near the top of the lower member or the base of the upper member. These fossils include remains of Procamelus (camel), Neohipparion and Pliohippus (horses), Plioceros (antelope) and Plionictis (weasel). The fossils are comparable to those found elsewhere in mammalian faunas of Hemphillian age (Woodburne and Golz, 1972); the age of the lower member of the Punchbowl Formation ranges from Clarendonian to about Hemphillian depend-ing on the exact stratigraphic position of the second fossil assemblage.

.CORRELATION OF PUNCHBOWL FORMATION, DEVIL'S PUNCHBOWL AND CAJON VALLEY, SOUTHERN CALIFORNIA.



EXOTIC COBBLE TYPES INDICATED BY SYMBOLS

L = MT. LOWE GRANODIORITE
PS = PELONA SCHIST
PO = "POLKA-DOT" CORDIERITE GRANITE
SV = "SIDEWINDER VOLCANIC SERIES"

(Hh), (C), (B), (H) = STRATIGRAPHIC POSITION OF FOSSIL MAMMAL REMAINS, CORRESPONDING TO EQUIVALENT LAND MAMMAL AGE.

Fig. 2

'he upper member of the formation is : east 830 m (2,500 ft.) thick. It adationally overlies the lower member ı generally contains, in contrast, er beds of coarse-grained sandstone ı more interbedded layers of grayish-en to greenish-brown biotitic arkosic ilstone, fine-grained sandstone and or beds of yellowish-to reddish-brown ilstone. The clastic composition of ; member is generally similar to that the lower, but there appear to be er clasts derived from the San Francis-:o Formation, and the polka-dot aite cobbles seem to be absent from but perhaps the lowest part of the er member. The upper unit also con-is an abundance of felsitic to porphy-ic volcanic rock clasts not found in lower. Fossils found in the upper ber, about 260 m above its base also of Hemphillian age: Procamelus, ohippus, Plioceros, and Osteoborus 0. cyonoides (bone-crushing dog). remaining stratigraphically higher ts of the type Punchbowl Formation are ated, but the age range of the whole nation is from Clarendonian to at st Hemphillian.

e of Deposition and Source

Pelka (1971) has indicated that the e Punchbowl Formation was deposited a narrow valley only a few miles wide that the clastic debris was derived n the east. Particularly, but not y, in the lower member of the forma-n the abundance and large size of the bles and boulders attest to at least iodic episodes of high stream compet-e. Inasmuch as many of the boulders similar to rocks now exposed in ion Ridge, this terrane may have been ource of part of the clasts in the chbowl Formation. Others came from lo presumably local outcrops of San ncisquito Formation, but the smaller bles of metavolcanic rock in the upper ber may have been transported over ater distances. If further studies er out the suggestion of Robinson and Woodburne (1971), these rocks may have originate winder Volcanic Series" n Katherine J. Barrows and A rows (written communication, 197 e above), suggest that this is not the case.

The type Punchbowl Formation appears to have been deposited by a stream or streams that flowed generally westward from the Mojave Desert across the present traces of the San Andreas and Punchbowl faults. At times, the competence of this drainage system was relatively high, and local relief (such as in Piñon Ridge) probably was fairly rugged.

CAJON VALLEY

General Statement

The Punchbowl Formation in Cajon Valley is a nonmarine succession about 2,600 m (8,000 ft.) thick. Although similar to the formation in the Devil's Punchbowl in that both display ledge-forming arkosic conglomeratic sandstones that weather with a pitted surface, the composition of the sandstones and the overall stratigraphy of the deposits in Cajon Valley differs from the rocks in the Devil's Punchbowl. As shown in Fig. 2, the formation is of different age in the two areas; Clarendonian and Hemphillian in the Devil's Punchbowl, Hemingfordian and Barstovian in Cajon Valley.

In Cajon Valley the Punchbowl Formation unconformably overlies marine rocks referred to the Vaqueros(?) Formation, and also rests on pre-Tertiary basement. The Punchbowl is unconformably overlain by the Crowder Formation. The age of the Crowder is not known; its upper part is gradational with deposits correlated with the Harold Formation, and on that basis is of Rancholabrean (late Pleistocene) age, although the lower part of the Crowder may be older than that. The marine Paleocene(?) San Francisquito(?) Formation also occurs in Cajon Valley, but it is in fault contact with the

Punchbowl rocks. See Noble (1954b) and Woodburne and Golz (1972) for additional comments on the stratigraphy of pre- and post-Punchbowl sediments in Cajon Valley.

In southern Cajon Valley, the Punchbowl Formation is truncated by the San Andreas Fault. The folded and faulted Tertiary succession is also bounded on the south and east by blocks of pre-Tertiary basement rock, and one of these stands up through the sedimentary cover near the junction of California State Highway 138 and Interstate 15. Near the top of this hill, marine rocks of the Vaqueros(?) Formation now occur at an elevation of over 1300 m (4,000 ft.). Farther northwest, the Cajon Valley Fault brings pre-Tertiary basement against the Punchbowl sediments; the sediments are less deformed in this part of the valley and generally dip northeastward before disappearing beneath the Crowder Formation or Quaternary alluvium.

Stratigraphy and Age

The lower part of the Punchbowl Formation consists almost completely of pale gray, white, or light pinkish-tan arkosic conglomeratic sandstone and sandstone beds that contain lenticular layering, cross stratification, and channel features typical of fluviatile sediments. The basal part of the succession, about 300 m (1000 ft.) thick, is generally weakly resistant and is unfossiliferous. The upper part of the conglomeratic sandstone sequence is well indurated and resistant, and forms conspicuous hogbacks and cliffs, the exposed faces of which bear conspicuous weathered pits and hollows up to 1 m in diameter. Toward the top of the section there are increasingly numerous interbedded lenticular layers of dark red to purple pebbly sandstone. The hogbacks are particularly well exposed in the central part of the valley along California State Highway 138. The resistant, hogback-forming, part of the sequence is about 600 m (1800 ft.) thick and has yielded in the upper few feet fossil remains of *Merychippus* cf. *M. tehachapiensis*, a horse elsewhere commonly found in mammalian faunas of late Hemingfordian age (Fig. 2). The underlying exposures of the Punchbowl are nc dated. These rocks are at least of Hemingfordian age, but might be older. Most of the coarser-grained clastic con stituents of these deposits (units Tp^1 and Tp^2 of Woodburne and Golz, 1972) ar mainly pebbles, cobbles and rarer boulc ers of granodiorite and quartz monzonit Next in abundance are small chips and often tabular fragments of dark, aphani tic, metamorphic rock. These materials are probably derived from basement rock exposures similar to those now found ir the western San Bernardino Mountains. Rare clasts of fine-grained sandstone m have been reworked from the Vaqueros(?) Formation that underlies part of this succession in southern Cajon Valley. Other clastic materials have an undeter mined origin, possibly being reworked from pre-existing Punchbowl sediments, but other rare metavolcanic clasts may have been derived from the "Sidewinder Volcanic Series", now exposed near Victorville, about 40 km to the northeast (Robinson and Woodburne, 1971).

A thinner unit, usually less than 300 m (1000 ft.) thick, gradationally overlies the resistant hogbacks. This unit (Tp^3 of Woodburne and Golz, 1972; and Red Beds of Fig. 2), is characterized by resistant arkosic conglomerate and conglomeratic sandstone beds that are interbedded with those of less resistant coarse-to fine-grained arkosic to biotitic sandstone and siltstone. The more resistant beds are light gray tan, or buff in color, but most of the less resistant fine-grained sandstone and siltstone beds are red to reddish brown. This unit is generally less prominent topographically than the resistant sandstone succession and is well exposed along the Southern Pacifi Railroad cuts adjacent to and east of California State Highway 138 in centra jn Valley. In the southern part of evalley, the red siltstone unit inter-ners with the hogback forming beds. his area, south of Sullivan's Curve he A.T.S.F. Railroad and southwest ajon Junction, fossil remains in-ding Merychippus cf. M. tehachapien-shave been found through most of the i, and it appears to be of late Hem-gordian age here. Farther northwest, a the Southern Pacific Railroad cuts s of Highway 138, other fossils, in-ding an oreodont, Brachycrus buwaldi, oar to be of early Barstovian age. hese age assignments are correct, ered siltstone unit of the Punchbowl ration is temporally diachronous, a tunexpected situation in an area ee fluviatile deposits were accumu-ting in a tectonically active environ-n. Most of the red siltstone and nstone sequences occur gradationally oe unaltered white conglomeratic nstones, and show progressive up-r alteration of hornblende and bio-t grains and increase in iron oxide an. These sequences are commonly oionally overlain by another unaltered ie conglomeratic sandstone. The red-lred units in this and other parts of ePunchbowl Formation are interpreted epresent a time of exposure of the dments to subaerial weathering odburne and Golz, 1972, p. 23-26).

n southern Cajon Valley, the red lstone unit is erosionally cut out by nterval of coarse-grained, biotitic, ksic conglomerate and conglomeratic nstone beds with a mottled maroon and a, grayish-buff, and more rarely, ie color. This unit (Tp^4 of Woodburne dGolz, 1972; SV opposite Red Beds of g 2) is about 230 m (700 ft.) thick, dcontains nearly equal amounts of aitic and metavolcanic rock. The tvolcanic rock clasts are thought to v been derived from the "Sidewinder lanic Series" (Robinson and Woodburne, 7). Large imbricated boulders of aodiorite can be seen in the mottled nlomerate unit, about one-half mile north of Cajon Campground, along the A.T.S.F. Railroad tracks. These and other imbricated cobbles and boulders in the Punchbowl Formation indicate that it was deposited by streams flowing generally to the southwest across the present traces of the San Andreas and Punchbowl Faults (Fig. 1). The age of this unit is not known. Because it stratigraphically truncates rocks of Hemingfordian age (red siltstone unit) in the area, and interfingers northward with drab colored rocks (see below) that contain fossils of Barstovian age, the mottled conglomerate unit probably is of that age as well. The mottled conglomeratic unit is laterally gradational with generally finer-grained Punchbowl deposits (noted above) and is considered to reflect the locus of a major stream channel in the Punchbowl Formation in southern Cajon Valley. In central and northwestern Cajon Valley a heterogeneous series of generally drab-colored deposits (see above) unconformably overlies the Hemingfordian to Barstovian age Red Bed sequence. The drab colored succession (Tp^5 of Woodburne and Golz, 1972) consists of mottled maroon and gray conglomerate and conglomeratic sandstone beds, interbedded with layers of purplish green and green coarse-to medium-grained, sandstone, freshwater limestone and more rarely, beds of dense black mudstone, and plant-bearing lignite. Most of the beds are poorly resistant. Fossils from the drab-colored succession include Archaeohippus, Merychippus, (horses), Aepycamelus (camel), Pseudoparablastomeryx (antelope) and a peccary. These fossils are thought to be of late, but not latest Barstovian age.

A clastic wedge (Fig. 2; Tp^{5a} of Woodburne and Golz, 1972) interfingers with the drab-colored sequence adjacent to the Cajon Valley fault in the northwestern part of the valley. The strongly upturned beds can be seen from the Oil Road turnoff of Highway 138. The constituents of this wedge-shaped unit are mainly angular cobbles and pebbles of granodiorite gneiss, gneiss, marble, and quartzite. The unit, at most about 960 m (2900 ft.) thick, appears to reflect uplift along the Cajon Valley Fault, with clastic debris having been shed eastward from the pre-Tertiary basement terrane now exposed west of the fault. No fossils are known from these beds; inasmuch as they interfinger with Barstovian age sediments of the drab-colored sequence, the clastic wedge is interpreted to be of that age.

The stratigraphically highest deposits of the Punchbowl Formation crop out in central and northwestern Valley where they unconformably overlie the drab-colored beds (SV of Fig. 2; Tp^6 of Woodburne and Golz, 1972), and are unconformably overlain by the Crowder Formation. The deposits are composed of white to pale gray and pale yellow conglomerate, conglomeratic sandstone, sandstone, and interbedded pale gray to reddish brown and brownish green fine-grained sandstone, siltstone and pale green mudstone. The sequence is about 300 m (900 ft.) thick, and contains abundant clasts of dark green and maroon porphyritic tuff and latite. No fossils have been found in this unit. Woodburne and Golz (1972) suggest that it is of Barstovian rather than Clarendonian age. Immediately subjacent rocks are of Barstovian, but not latest Barstovian, age.

Mode of Deposition and Source

Marine rocks of Paleocene(?) and late Oligocene age occur in Cajon Valley (Fig. 2), but by the Hemingfordian or possibly somewhat earlier, nonmarine conditions prevailed. Based on the available paleocurrent data, the Punchbowl Formation in Cajon Valley was deposited by a stream or streams that flowed generally southwestward across the present traces of the San Andreas and Punchbowl faults. The Cajon Valley basin eventually accumulated a succession of largely fluviatile deposits that attained a thickness of nearly 2600 m (8000 ft.). The lenticular bedding, local unconformities and conglomeratic channels in the lower 600 m (2000 ft.) of section indicate that deposition wa episodic, rather than continuous at a given location. The large size of the cobbles and boulders attest to periods of relatively high depositional energy By the late Hemingfordian and locally in the early Barstovian (Red Beds) the were longer periods of reduced depositional energy, and many of the fine-grained sandstone and siltstone beds v subaerially oxidized. Many of the deposits in the upper 2000 m (6000 ft.) the Punchbowl Formation can be interpreted to represent sets of sequences that become finer-grained upward. The uppermost siltstone layers of one sequence are commonly unconformably over lain by beds of conglomeratic sandsto that comprise the base of the next sequence. The beds of lignite and limestone probably reflect local ponding, some of the drab green-colored siltst layers also may have been formed in a lacustrine environment. The interval of quieter deposition in the upper 20 m (6000 ft.) of the Punchbowl Formati may reflect episodic partial or compl damming of the Cajon Valley streams b tectonic activity on the San Andreas Punchbowl faults, but this remains to demonstrated. Local tectonic activit on the Cajon Valley Fault during the Barstovian, however, is shown by the clastic wedge in the northwestern par of the valley. The very coarse-grain textures and imbricated boulders of t mottled conglomerate unit in southeas ern Cajon Valley are interpreted to mean that a vigorous stream flowed so westward across the traces of the San Andreas and Punchbowl faults at about the same time as, or perhaps slightly earlier than, the deposition of the clastic wedge to the northwest.

With the exception of the clastic wedge, the available evidence indicat that the Punchbowl Formation in Cajon Valley was deposited by streams that

ped southwestward. Many of the grano-
oite boulders and cobbles probably
r derived from the adjacent San Ber-
rino Mountains and the dark-colored
is of fine-grained metasedimentary
c could have come from the San Ber-
rino terrane, or pre-Tertiary sedi-
ns that now also occur in the vicin-
yof Victorville about 40 km (25 miles)
he northeast. Some of the metavol-
nc cobbles that occur in the Punch-
w Formation may have been contributed
he "Sidewinder Volcanic Series"
binson and Woodburne, 1971).

SUSSION

hether the Punchbowl Formation in
jn Valley deserves to be designated
hat name depends on the likelihood
a the Cajon Valley basin was related
hat of the type Punchbowl Formation.
e though the two sequences differ in
eand stratigraphic detail, they are
r similar to each other than to any
he other rock units in this general
e. "It is conceivable that the
eent Punchbowl terranes represent
ferent parts of a more or less con-
nous depositional basin in which the
nral Punchbowl type of deposition and
s-Punchbowl deformation, began earli-
n the southeast [Cajon Valley] but
sed longer in the northwest [Devil's
nhbowl]" (Woodburne and Golz, 1972,
0). Marine rocks of Paleocene age
o definitely proven in Cajon Valley)
tof different lithology occur in each
he two areas, so it is at least
sible that the Devil's Punchbowl was
poximately aligned with Cajon Valley
hat time. The considerably different
s-Paleocene tectonic and depositional
sories of the two areas appear to
l out the possibility of their juxta-
stion after the Paleocene, at least
he various times when deposition
nown to have occurred. If this is
ecase, and if Tertiary slip on the
nhbowl and San Andreas faults was
gt lateral, the Devil's Punchbowl
s have been located somewhere northwest of Cajon Valley when either of the Punchbowl successions were being deposited. Woodburne and Golz (1972, p. 40) suggest that the Devil's Punchbowl could have been within 16 or 25 km (10 or 15 miles) of its present location in the Clarendonian and Hemphillian and still be in a position to receive its clastic constituents without interference from rock terranes exposed by tectonic events in Cajon Valley which apparently was undergoing uplift and erosion at that time. Should this scheme be viable, there may be some justification for retaining the Punchbowl designation for the Cajon Valley succession. The other alternative, that in the Clarendonian or Hemphillian the Devil's Punchbowl was located some distance to the southeast of Cajon Valley, might make it sufficiently unlikely that the two successions are related so as to require a new formation name for the rocks in Cajon Valley. The answer ultimately rests on the amount and timing of right-lateral slip on the Punchbowl and San Andreas faults. Some aspects of this problem are discussed in Woodburne (1975a).

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THE SAN ANDREAS FAULT ZONE IN THE JUNIPER HILLS QUADRANGLE, SOUTHERN CALIFORNIA

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ETRACT

Detailed geologic mapping in progress r the Juniper Hills quadrangle is the is for a discussion of the geology of San Andreas fault zone which ranges m the Little Rock fault on the north the Carr Canyon and Southern Nadeau lts on the south. Right-lateral dis- cements of five miles for Quaternary ks and 10 miles for Tertiary units are erred from this mapping. Western ies Punchbowl Formation occurs both th and south of the San Andreas but y north of the Northern Nadeau fault. e facies Punchbowl Formation occurs y between the Southern Nadeau and Carr yon faults. Tertiary units of uncer- n correlation, possibly younger than upper member of the type Punchbowl mation, are discussed.

TRODUCTION

A detailed geologic map of the north- n two-thirds of the Juniper Hills quad- ngle is being prepared in financial operation with Los Angeles County. This adrangle lies between the excellent ologic maps of Levi Noble (Pearland adrangle, 1953; Valyermo Quadrangle, 54a). The San Andreas fault zone, llowing Noble's designation, ranges in dth from about 6,000 feet on the west about 2,000 feet on the east. Mapping large-scale aerial photos, including w-sun and color, has made it possible depict both the detailed geology of e fault zone and the surficial features ee Fig. 1) that define the most recently tive traces of the San Andreas fault. cation of buried faults has been in- rred from results of several magnetic d seismic surveys. Figure 1 is generalized from 1:9,600 scale maps. Structural data and differentiation of most of the Quaternary units has been omitted because of the small scale of the figure.

GEOLOGY

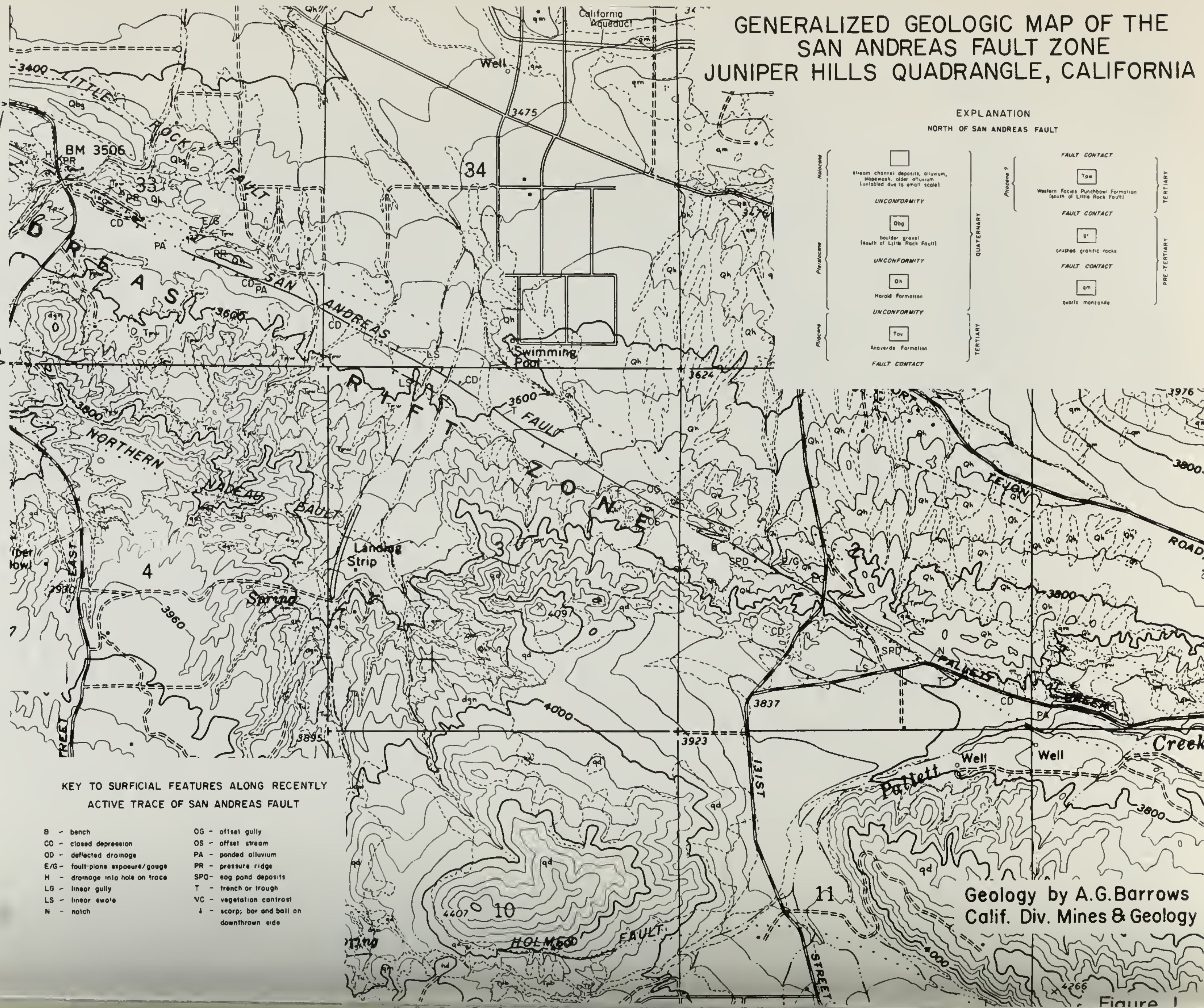
General Statement

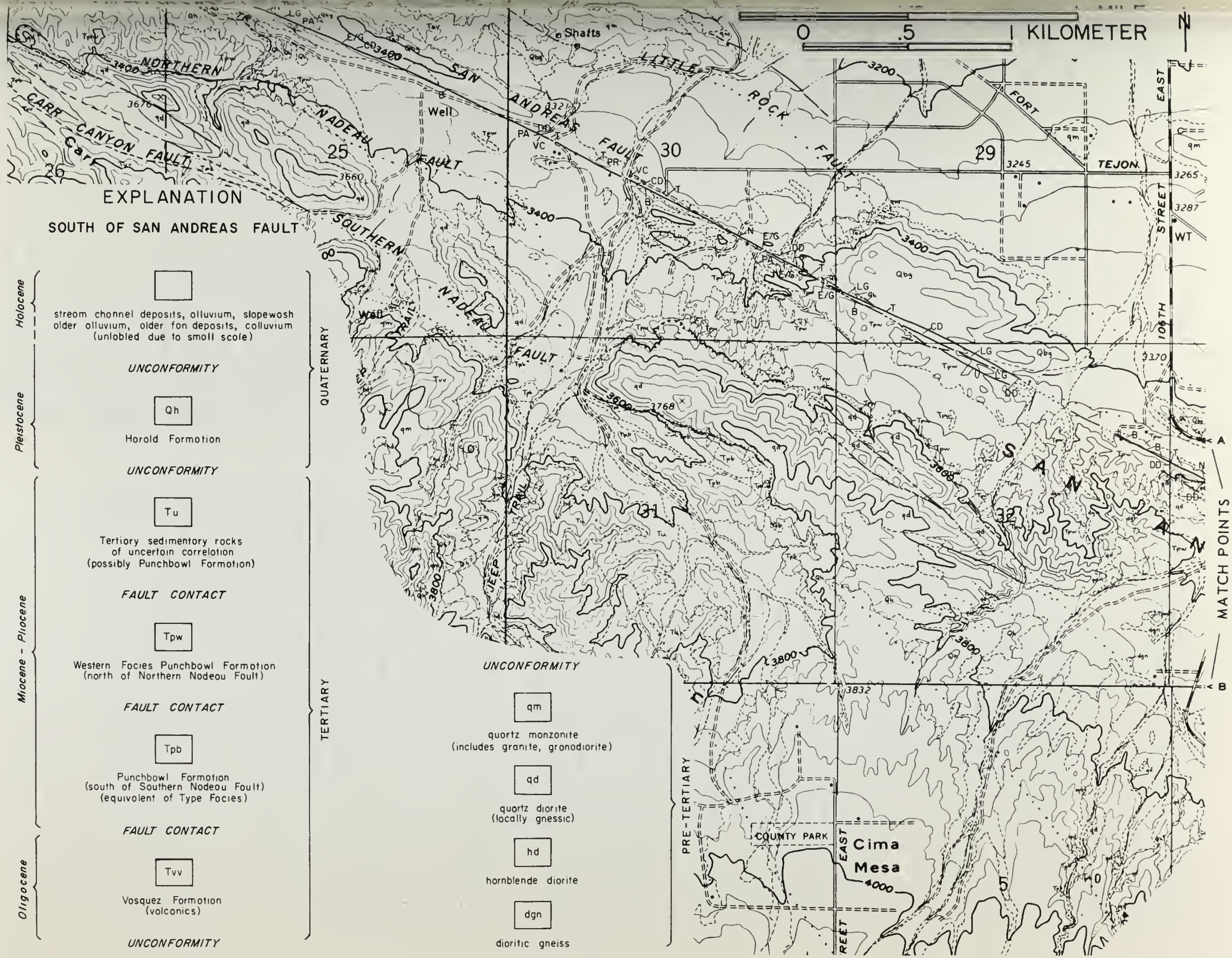
It is convenient to separate the discussion of the geology into sections dealing with each side of the San Andreas fault because of the dissimilarity of the stratigraphy across the fault (Fig. 1). The northern boundary of the San Andreas fault zone is considered the Little Rock fault (Noble, 1953), although there is evidence of young faulting north of that fault that suggests the zone may be as wide here as it is at Palmdale.

On the west the Carr Canyon fault is the southern boundary of the San Andreas fault zone, whereas on the east the Northern Nadeau fault is defined as the boundary. It appears that the Carr Canyon fault, which diverges southward going southeast, may be the western continuation of the Punchbowl fault of the Valyermo area. Likewise, the Southern Nadeau fault may be the western continuation of the Holmes fault of the Valyermo area. The Northern Nadeau fault merges with the San Andreas fault east of the Juniper Hills quadrangle.

North of the San Andreas Fault

Northward from the Little Rock fault, a batholith of leucocratic granitic rocks, predominantly quartz monzonite, containing inclusions of metasedimentary rocks including skarn, and small bodies of locally layered and orbicular gabbro, extends into the Mojave Desert.


GENERALIZED GEOLOGIC MAP OF THE
SAN ANDREAS FAULT ZONE
JUNIPER HILLS QUADRANGLE, CALIFORNIA
EXPLANATION
NORTH OF SAN ANDREAS FAULT
Holocene
stream channel deposits, alluvium, slopewash, older alluvium (unlabled due to small scale)
UNCONFORMITY
Pleistocene
Qbg
boulder gravel (south of Little Rock Fault)
UNCONFORMITY
Qh
Harold Formation
UNCONFORMITY
QUATERNARY
Pliocene
Tav
Anaverde Formation
TERTIARY
FAULT CONTACT
Pliocene ?
FAULT CONTACT
Tpw
Western Facies Punchbowl Formation (south of Little Rock Fault)
TERTIARY
FAULT CONTACT
crushed granitic rocks
FAULT CONTACT
qm
quartz monzonite
PRE-TERTIARY
KEY TO SURFICIAL FEATURES ALONG RECENTLY ACTIVE TRACE OF SAN ANDREAS FAULT
B - bench
CD - closed depression
DD - deflected drainage
E/G - fault-plane exposure/gouge
H - drainage into hole on trace
LG - linear gully
LS - linear swale
N - notch
OG - offset gully
OS - offset stream
PA - ponded alluvium
PR - pressure ridge
SPD - sag pond deposits
T - trench or trough
VC - vegetation contrast
scarp; bar and ball on downthrown side
MATCH POINTS
LITTLE ROCK FAULT
SAN ANDREAS FAULT
RIFT ZONE
NORTHERN NADEAU FAULT
TEJON ROAD
PALLETT CREEK
HOLMES FAULT
131ST STREET
California Aqueduct
Swimming Pool
Landing Strip
Spring
Well
BM 3506
Geology by A.G.Barrows
Calif. Div. Mines & Geology
Figure 1



0 .5 1 KILOMETER
N
MATCH POINTS
A
B
NORTHERN NADEAU FAULT
CARR CANYON FAULT
Carr
SAN ANDREAS FAULT
LITTLE ROCK FAULT
SOUTHERN NADEAU FAULT
FORT TEJON
EAST 106TH STREET
JEEP TRAIL
COUNTY PARK
Cima Mesa
Shafts
Well
SAN
25
26
29
30
31
32
5
3200
3245
3265
3287
3370
3400
3600
3660
3670
3768
3800
3832
4000
WT
EXPLANATION
SOUTH OF SAN ANDREAS FAULT
Holocene
Pleistocene
QUATERNARY
stream channel deposits, alluvium, slopewash
older alluvium, older fan deposits, colluvium
(unlabled due to small scale)
UNCONFORMITY
Qh
Harold Formation
UNCONFORMITY
Miocene - Pliocene
TERTIARY
Tu
Tertiary sedimentary rocks
of uncertain correlation
(possibly Punchbowl Formation)
FAULT CONTACT
Tpw
Western Facies Punchbowl Formation
(north of Northern Nadeau Fault)
FAULT CONTACT
Tpb
Punchbowl Formation
(south of Southern Nadeau Fault)
(equivalent of Type Facies)
FAULT CONTACT
Oligocene
Tvv
Vasquez Formation
(volcanics)
UNCONFORMITY
PRE-TERTIARY
UNCONFORMITY
qm
quartz monzonite
(includes granite, granodiorite)
qd
quartz diorite
(locally gneissic)
hd
hornblende diorite
dgn
dioritic gneiss

South of the Little Rock fault the oldest rocks exposed are small "slivers" of sheared diorite and extremely crushed white granitic rocks adjacent to the San Andreas fault. Two distinctly different Tertiary non-marine sedimentary units occur within the tectonic block bounded by the Little Rock and San Andreas faults. Red, white, and buff arkosic sandstone and brown, gypsiferous clay shale constitute the lower-middle Pliocene Anaverde Formation. The easternmost exposure of this formation is a roadcut along 106th Street where Anaverde clay shale is bounded on the south by a fault that branches from the San Andreas. Eastward from just west of 106th Street small outcrops of smashed (offset cobbles) and crushed white sandstone and pebbly sandstone appear that is correlated with material mapped south of the San Andreas fault as Western Facies Punchbowl Formation. Differences between western and type facies Punchbowl Formation are discussed below. Western Facies rocks are nowhere seen in contact with type Punchbowl and their age is unknown. It may be younger than type Punchbowl and possibly even coeval with Anaverde Formation from which it is also separated by faults.

Poorly bedded, light-brown, moderately consolidated siltsone through pebble conglomerate of the Harold Formation is abundant east of 106th Street. Overlying both Anaverde and Harold formations is a distinctive red-brown weathering boulder gravel characterized by large (up to 6 feet) well-rounded boulders and cobbles of porphyritic granodiorite ("Mt. Lowe" type) and black hornblende gabbro and hornblendite. The easternmost extent of this gravel is one-half mile east of 106th Street. Because the boulder gravels were derived from coarse piedmont fan deposits in the Pearland quadrangle (Noble, 1953) west of Littlerock Creek they are inferred to have been offset right-laterally about five miles during movements of the block that lies between the San Andreas and Little Rock faults.

South of the San Andreas Fault

The pre-Tertiary rocks are more var south of the San Andreas fault. Hornblende quartz diorite, correlated with Pinyon Ridge granodiorite of the Valyer quadrangle (Noble, 1954a), is widesprea especially in large, wedge-shaped bloc bounded by segments of the Nadeau faul system. Bodies of dioritic gneiss and related metaigneous rocks locally exhi extremely complex structures. East of 106th Street inclusions of metamorphic rocks (mica schist, marble) are presen the diorite. Granite also crops out there. South of the Carr Canyon fault quartz monzonite to granodioritic rock have intruded black hornblende-rich diorite.

The oldest Tertiary rocks (in Fig. are Oligocene andesitic volcanic rocks the Vasquez Formation that intruded an were deposited upon weathered quartz m zonite south of the Carr Canyon fault. Nowhere in the Juniper Hills area do known Punchbowl rocks rest depositiona upon Vasquez volcanics; these two unit are everywhere separated by the Carr Canyon fault.

Punchbowl Formation sandstone, pebb sandstone, and minor red siltstone and nodular limestone, similar in clast co position to the upper member of the Pu bowl in the Valyermo quadrangle is rec nized only north of the Carr Canyon fa and south of the Southern Nadeau fault

Between the San Andreas and Norther Nadeau faults the only Tertiary unit i Western Facies Punchbowl Formation. T most important difference between west and type facies Punchbowl Formation is the dissimilarity of composition and te proportions of cobbles and pebbles in each. The Western Facies contains cla types not found in the type facies an exhibits greater variability among str graphic units. Distinctive rock type such as alkali syenite, blue-quartz granite, and serpentinite are present addition to common leucocratic pluton rocks, and gray-green (Pelona-like) m schist. Both facies contain metavolcanic clasts and abundant unmetamorphosed volcanic clasts ranging from rhyolite to andesite. Most and possibly all of the metavolcanic clasts were reworked from conglomerate lenses in the Paleocene San Francisquito Formation (especially the "eta" latite and quartz latite ash-flow tuffs). Some of the unmetamorphosed volcanic clasts were hydrothermally altered and the vitric portions of at least one clast type have been weakly to moderately zeolitized to mordenite and/or clinoptilolite. Two unmetamorphosed types were derived from the San Francisquito Formation. Some andesites resemble those of the Vasquez Formation, but the bulk of the volcanic clast types are not similar to rocks of the Vasquez Formation, San Francisquito Formation or the Sidewinder Volcanic Series. In addition to the above, both facies contain angular to well-rounded clasts of sandstone and pebbly conglomerate derived from the San Francisquito Formation (clast petrography by Katherine J. Burrows).

The easternmost exposures of the Western Facies Punchbowl Formation, south of the San Andreas fault, are 1.2 miles west of Pallett Creek. North of the San Andreas fault, a sliver of similar rocks exposed in a roadcut opposite Jackson Lake (near Big Pines) is inferred to have been offset along the fault 10 miles from the Juniper Hills quadrangle. Rocks mapped by Noble as Western Facies Punchbowl Formation in the Mountain Brook Ranch area of the Valyermo quadrangle do not resemble typical Western Facies rocks as defined by Noble (1954a) and are probably Quaternary older alluvial units possibly related to Harold Formation.

Tertiary sedimentary rocks of uncertain correlation, predominantly soft, red and light brown siltstone with subordinate pebbly sandstone, are well exposed northwest of Cima Mesa and, off Figure 1, north of Cima Mesa Road. These rocks may belong to a facies of the Punchbowl Formation that is younger than the upper member of the type facies. In section 31 they are puzzling because they appear to overlie the Carr Canyon fault which to the west cuts type Punchbowl Formation. An area of brown siltstone with minor maroon concretion-bearing layers in the southeast quarter of section 4 also differs from typical Punchbowl Formation. These rocks were called Vaqueros Formation by Noble (1954b) but they are unlike Vaqueros rocks near Cajon Valley and do not appear to be of marine origin. Unfortunately, determination of age and correlation of these units is difficult because no useful fossils have been found in any of the Tertiary rocks within the Juniper Hills area.

Harold Formation, the oldest Quaternary unit, is widespread south of the San Andreas fault. It is typically silty, loosely to moderately consolidated, and contains abundant gravel layers whose composition generally reflects the lithology of nearby underlying source rocks such as the Punchbowl and Vasquez formations. As Noble pointed out, Harold Formation was deposited on a surface of much lower local relief than exists today. Where bedding is well developed dips are typically gentle. The present distribution of Harold Formation implies that it may have covered much of the area in Figure 1. Accordingly, faulting, uplift, and erosion since Harold time has been extensive.

Several older Quaternary units, not labelled in Figure 1, have been mapped in the Juniper Hills quadrangle. These post-Harold units are generally coarse grained, reflecting the Pleistocene rise of the San Gabriel Mountains, and serve as records of continued tectonic unrest in this area.

ACKNOWLEDGEMENTS

Reviewed by James K. Kahle and Cliffton H. Gray.

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RECENT FAULT FEATURES AND RELATED GEOLOGY, LEONA VALLEY AREA, SOUTHERN CALIFORNIA

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Research sponsored by the U. S. Geological Survey, Department of the Interior, under U.S.G.S. Grant Numbers 14-08-0001-G-74 and 14-08-0001-G-153.

ABSTRACT

Detailed mapping along 11.8 miles of the San Andreas fault zone in Leona Valley has revealed a variety of distinctive Quaternary units and has provided evidence for renaming part of the Anaverde Formation. In most places the San Andreas fault has been accurately located and the surprisingly abundant recent fault features, which were either formed or enhanced in 1857, have been recorded. Branch faults have been mapped in one area forming a zone of faulting 50-150 feet wide. Pelona Schist is thrust over rocks of late Tertiary age along a fault mapped subparallel to the San Andreas trend. A brief discussion of localities where the San Andreas fault is well exposed and where fault features are plentiful is included.

INTRODUCTION

Detailed mapping of recent fault features and related geology is being completed along 11.8 miles of the San Andreas fault zone in Leona Valley. Work is continuing eastward on the 12 mile stretch between Leona Valley and the Juniper Hills quadrangle but is not discussed here. This project is partially supported by Los Angeles County and the U.S.Geological Survey. Mapping was done on low-sun and color air photos at nominal scales of 1:6,000 or 1:12,000. While the work was primarily aimed at accurate location of the most recently active fault traces and related physiographic features, it has been necessary to map the Quaternary and Tertiary rocks along the fault in considerable detail. This report stresses the number and density of recent fault features present along the San Andreas but a brief discussion of some of the rocks involved in repeated older movements is included. Figure 1 shows most of the fault features found in the area but only the generalized terrane, which may be covered locally by thick alluvium, is labeled by name. Locations on the map are keyed to section numbers only, which do not repeat in the three townships covered. Twenty three bucket auger and two core-drill holes were drilled providing valuable data on depth of alluvium and concealed faults. Magnetic and low-energy seismic profiles were run but, in some cases, the results did not agree with the drilling data and these are being further analyzed. One core-hole drilled in the large sag-pond in the SW$\frac{1}{4}$ sec. 1, penetrated 93.5 feet of alluvium and contained wood-fragments from which radiocarbon dates may be obtained. Samples for pollen analysis taken from this core and from various other rock types are still being studied.

GEOLOGY

Pre-Tertiary crystalline rocks crop out on both sides of the San Andreas fault zone in this area and, though not mapped in detail, they were studied carefully so that the source or sources of the Tertiary and Quaternary units might be identified. The Pelona Schist has been adequately described by previous workers, notably Wallace (1949), Muehlberger and Hill (1958) and Dibblee (1961, 1967) and crops out only south of the San Andreas at the east end of the map area. The debris derived from the Pelona Schist in and adjacent to the map area, has two important characteristics. Muscovite schist clasts, with a distinctive silvery sheen, are very abundant and commonly are rounded to well-rounded blade or discoid in shape. Talc-actinolite and chlorite-albite schist is also very common.

The Portal Schist which crops out across the length of the area north of the San Andreas fault zone, was named and described in detail by Evans (1966). Most other authors have referred to these rocks as Pelona Schist but the differences described by Evans are believed to be significant. Typically, biotite rather than muscovite prevails and the clasts derived from outcrops in and adjacent to the map area are sub-rounded to angular and blocky to sub-spherical in shape. Blade or disc shaped clasts do not form because the source rocks are not well foliated and are strongly shattered.

The gneiss and diorite complex has been described by Wallace (1949),Dibblee (1961) and Evans (1966). Most of the debris being shed by this complex now is granular because weathering has deeply penetrated the parent rock. In the geologic past, however, the complex apparently produced pebble- and cobble-size debris which survived long enough to be deposited in some of the younger units described below. Much of this unit is covered by alluvium and fan deposits. Drilling south of the fault which runs between Messer Ranch and Bouquet Canyon Road, about 2,500 feet south of the San Andreas, has shown at least 70 feet of alluvium offset vertically against gneiss which crops out north of the fault.

The Tertiary Anaverde Formation has been mapped in detail. Throughout most of the area it lies between the north branch and the main branch of the San Andreas fault. On the extreme western end of the area a large sliver occurs south of the main trace. The Anaverde Formation has been subdivided, following Dibblee (1961), and includes, as a basal member, a hornblende diorite-rich breccia which appears to be partly sedimentary and partly tectonic and crops out mainly adjacent to the north branch of the San Andreas.

Tertiary rocks which crop out south of the San Andreas fault on the eastern end of the map area have been mapped as Anaverde Formation by Wallace (1949), Dibblee (1961) and Evans (1966). These rocks are here named Ritter Formation on the basis of the composition of the clasts it contains. Members have not been recognized in the formation. The Ritter Formation consists of white to lig gray conglomeratic arkose beds and fine- to coarse-grained beds of arkosic sandstone interbedded with dark gray to brown biotitic siltstone and very fine-grained sandstone. The cobbles, pebbles and grains of these rocks appear to have been derived exclusively from the gneiss-diorite complex. The Ritter Formation contains few clasts similar to those foun in the Anaverde Formation elsewhere nor does it contain any schist or volcanic debris. Indeed, it is so closely allied to the gneiss-diorite complex that the soil or slopewash from either unit is nearly identical and it is commonly necessary to dig through the surface material to identify these units.

The Ritter Formation crops out from Bouquet Canyon Road eastward to the edge of the map area and has been seen by the author as far east as City Ranch (about one mile). It is bounded on the north b the San Andreas, except where small slivers north of the main trace are show on the map. In the central part of its outcrop area, the Ritter Formation is in probable thrust-fault contact with the gneiss-diorite complex. From the bounda between sec. 23 and sec. 24 eastward Pelona Schist is thrust northward over t Ritter Formation. In most places the Ritter Formation is poorly exposed and i covered by alluvium and fan deposits or older terrace gravel. It may be as much as 1,500 feet thick, if not repeated by faulting, but the top and bottom are not exposed. It is in fault contact with al adjacent rocks and is named after Ritter Canyon in the center of sec. 22. It is not well exposed where it is inferred to be thickest, between Ritter Canyon and Bouquet Canyon Road, so the type section is tentatively placed along the powerlin road going south from Elizabeth Lake Roa near the center of the E½ of sec. 23, T.6 N., R.13 W. The Ritter Formation is well exposed for about 800 feet along th

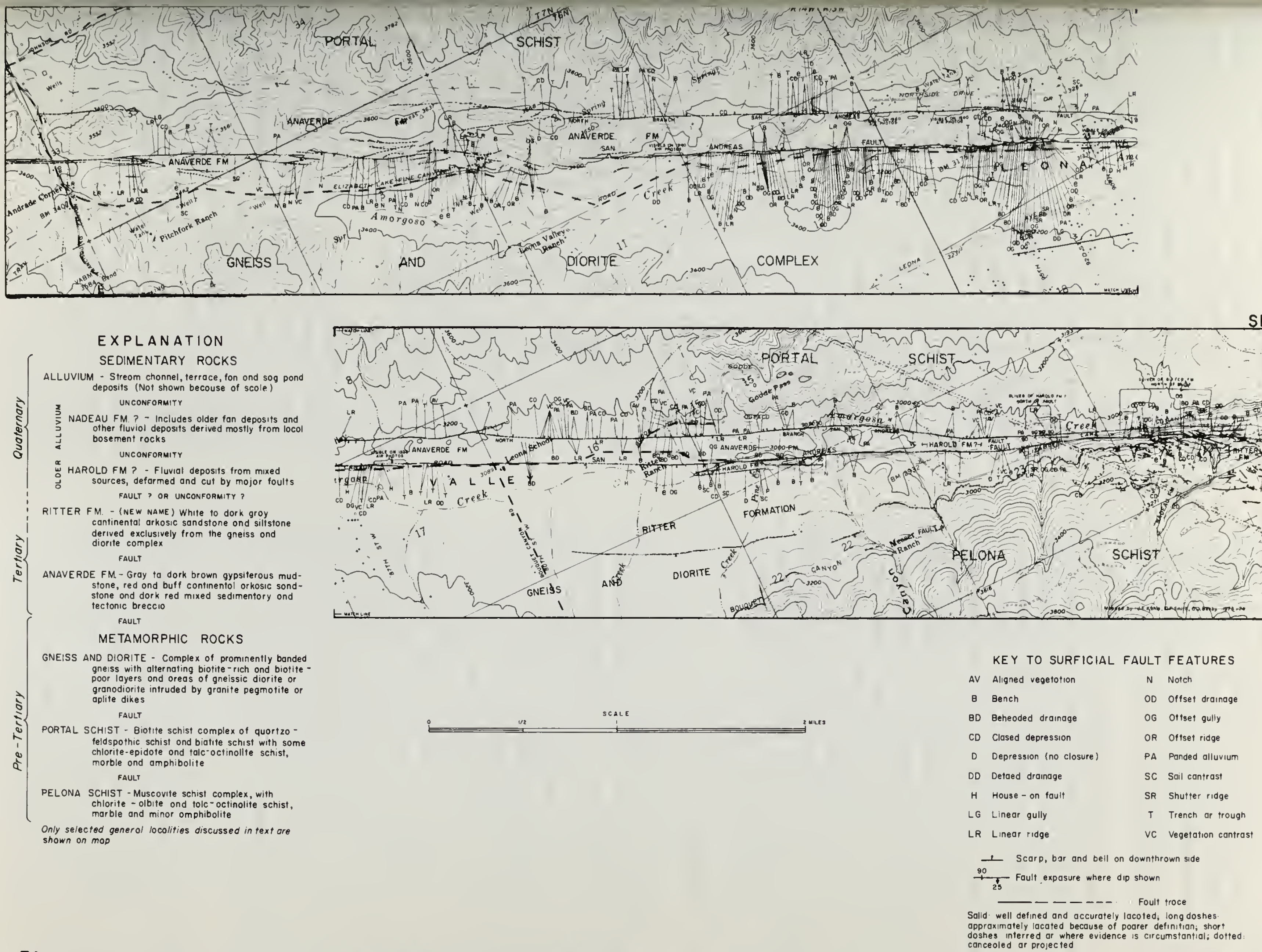

Figure 1. Annotated map of the San Andreas fault zone, Leona Valley area, southern California.

powerline road and its position under the Pelona Schist is clear. The age of the formation is unknown but it appears to be unconformably overlain by older alluvium in several places suggesting a late Pliocene or early Pleistocene age.

The Quaternary rocks in the area have been divided into a number of units on the basis of contained clast composition and percentage, but are not shown on Figure 1. Basically, three types are recognized; those possibly equivalent in age to the Harold Formation and the Nadeau Formation, mapped by Noble (1953) in the Pearland quadrangle, and younger alluvium. Units shown on Figure 1 as Harold Formation? and Nadeau Formation? are only parts of the widespread older alluvium in the area that have been selected to show their relationship to faulting. These units are discussed under fault features.

FAULT FEATURES

The density of fault features in the Leona Valley area is much greater than at first realized. Air photo interpretation is very important for accurately locating such features and establishing the continuity of fault traces. Older air photos of 1928 and 1940 vintage were invaluable where cultivation or construction has since obliterated the evidence. However, many of the features shown on Figure 1 could only be located on the ground and, particularly where obscured by sparse vegetation, were not visible on 1:6,000 scale low-sun photos. Many of the smaller features are presumed to have formed in 1857, the most recent reported movement on this portion of the San Andreas fault.

At the eastern end of the area in the SW¼ sec. 24, within 150 feet of the main trace, subtle fault features are abundant. The map shows only selected features, mostly along the main fault, but the small branch faults shown represent chains of miniature closed depressions (less than 5 feet in diameter) along small linear scarps (less than one foot relief) or lines of pebbles and cobbles which mark an abrupt change in slope angle. These branch faults diverge fro the trend of the main trace by 10-20 degrees, oriented as Riedel shears on a right-lateral system (Tchalenko, 1970). Some can be followed as far as 800 feet but most are shorter than 300 feet and commonly separate different rock types. These form a zone of faulting 50-150 fee wide centered on the main trace. Simila branch faults occur elsewhere along the San Andreas but are well preserved at th location because of very little erosion due to low local relief.

Older alluvium marked Nadeau Formatic on the map near the SW corner of sec. 24 consists of well-rounded coarse gravel derived exclusively from Pelona Schist a deposited on it. This location is near the western limit of these distinctive rocks which are presumed to have been deposited at a time when large amounts of schist debris were being washed across the San Andreas. Similar deposits were mapped by Noble (1953) in the Palmdale area, north of the San Andreas. This relationship was recognized by Dibblee (1960) but detailed mapping of these Quaternary units being done in the Palmdale area is defining this offset more closely. Other older alluvium, called Harold Formation? on the map, occurs at three locations and appears to be displaced by both the main San Andreas and the north branch of the San Andreas.

Good exposures of both branches of tl San Andreas are indicated by attitudes shown on the map. On the main trace ne the center of sec. 23 one excellent exposure reveals alluvium and rocks of th Anaverde Formation juxtaposed. It is short walk from here to the north brancl where rocks of the Harold Formation? (north of the fault) are faulted agains alluvium (south of the fault) and are e posed three places in stream cuts. At the center of the boundary between sec. and sec. 22 rocks of the Harold Formati are exposed and have been faulted ainst rocks of the Anaverde Formation.

About 1,500 feet along Godde Hill Road rth of the junction with Elizabeth Lake ad one can turn right (southeast) on a rt road and drive along the north anch for about 0.6 mile viewing many ult features.

From just west of Bouquet Canyon Road the corner of sec. 1, sec. 2, sec. 11, d sec. 12, Elizabeth Lake Road paral-ls the San Andreas fault. It is easily cognizable,except where construction s obliterated the surface evidence, and n be reached by a short walk north from e road. The areas where a high density fault features is shown on the map may ggest some places to stop. About 1,500 et west of the town of Leona Valley the in fault is well defined by numerous ult features. About a mile farther st, the fault is very close to the road d a large offset drainage channel marks e approximate center of a stretch along e fault which starts at the boundary tween sec. 7 and sec. 12 and extends r about 2,000 feet. The variety of atures visible here makes it well rth the walk. Offset gullies along is section are not always consistent t some of the smaller ones are pre-med to have formed before the last vement on the fault in 1857 and seem to offset about the same amount, on the der of 15 feet.

KNOWLEDGMENTS

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THE SAN GABRIEL FAULT AND RIDGE BASIN, SOUTHERN CALIFORNIA

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ABSTRACT

During Pliocene time, the San Gabriel fault, now inactive, was a major strand of the San Andreas fault system and moved nearly continuously for several million years. Ridge Basin formed during this interval and apparently subsided as it traveled laterally alongside of a rising region near present Frazier Mountain. From this source area, coarse debris spilled northeastward across the fault scarp and was strewn out to form the Violin Breccia. The breccia, along with other stratigraphic units constituting the thick section filling Ridge Basin (11,000 m or 36,000 ft) was deposited in beds overlapping toward the northwest. The oldest units (uppermost Miocene) of the Violin Breccia display about 30 km (18 mi) of right slip from their source area and about 4500 m (15,000 ft) of dip slip. In addition, on the southwest side of the fault, marine upper Miocene conglomerates (Modelo Formation) of the Ventura Basin sequence are displaced about 35 km (22 mi) from their source in the western San Gabriel Mountains. Older rocks and structural trends show a total of right slip of about 60 km (38 mi). The fault may have originated in the early Miocene, but was clearly active by the late Miocene.

As shown by unconformities, the San Gabriel fault died near the beginning of Pleistocene time and somewhat later than faults trending into Ridge Basin on the east such as the Clearwater and the Liebre. In the mid-Pleistocene, the Frazier Mountain thrust system was born, culminated, died and then was folded. Displacement on the San Andrea fault, adjacent to the north, vigorously ensued and continues today.

INTRODUCTION

The San Gabriel fault was a major branch of the San Andreas fault system, as shown by geologic relations along its northwestern part (Fig. 1) (Crowell, 1950, 1962). Here we shall review these briefly, summarizing information previously published but also drawing on data not yet in print. The interpretation of the fault's history is largely based on a reconstruction of its role in the formation of Ridge Basin. This is shown by the facies of the later Cenozoic sediments contained within the basin, by crosscutting relations of faults, and by unconformities. Following the origin of the San Gabriel fault in the early or middle Miocene, it was active continuously from late in the Mioc and died at the beginning of the Pleistocene. The fault moved through time primarily by right slip but with a marked dip-slip component.

THE SAN GABRIEL FAULT

At the surface, the San Gabriel fault zone can be followed as a continuous break for 130 km (80 mi from a point south of Tejon Pass to within the San Gabriel Mountain and then along two branches to nea San Antonio Canyon, about 20 km (12 mi) west of the San Jacinto an San Andreas faults in Cajon Pass (see map in guidebook pocket). Ol- er rocks along its course are crus- ed but the fault itself is discret and marked by hard black gouge up to several meters in thickness (Ehlig, 1973). In the Ridge Basin region, the fault dips about 70° N.E. but elsewhere it is nearly vertical with a straight trace across rugged terrain. Across the lowlands between Castaic and Newall -- a region immediately underlain by alluvium and terrace deposits and in turn below these, by Plio-Pleistocene Saugus Formation -- the strata are younger than most of the movements on the fault zone. Its trace here is marked by a zone of braided small faults and steep dips within adjacent strata.

Within the western San Gabriel Mountains the fault zone branches. The northern branch continues on eastward and offsets several steeply dipping basement contacts about 22 km (14 mi) (Ehlig, 1966). Farther to the east the fault is displaced to the left by the younger north-northeast-trending San Antonio fault for about 3 km (2 mi), and trends on eastward into the Cajon Pass region. The southern branch extends southeastward through the basement terrain of the San Gabriel Mountains, and then bends easterly to join the fault zone fronting the range on the south (Dibblee, 1968). Although there is a mismatch in the basement terrain across the southern branch of the San Gabriel fault, substantiation of a suspected right-slip of about 38 km (24 mi) has not yet been recognized. This amount of displacement is presumably needed to bring the total right slip on the combined two branch faults to the 60 km (38 mi) recognized on the northwestern part of the San Gabriel fault zone. Recent displacements along the south front of the San Gabriel Mountains have resulted in thrust separations (Proctor and others, 1970) accompanying the elevation of the mountains. Several active faults in this region, including the Raymond and Cucamonga faults (Morton and Yerkes, 1974) have apparently moved more recently than parts of the Malibu Coast - Santa Monica fault system.

On the northwest the San Gabriel fault is overlapped by Plio-Pleistocene beds of the Hungry Valley Formation (Crowell, 1950 (Fig. 1). Along the trend of the fault a few kilometers on farther to the northwest these beds in turn are folded and overturned beneath branches of the Frazier Mountain system (the Dry Creek thrust; Fig. 1, loc. F), and the steep northeastern slope of Frazier Mountain itself is probably the uplifted, rotated, and exhumed San Gabriel fault scarp. Before the Frazier Mountain thrust system originated in Pleistocene time the San Gabriel fault no doubt extended on trend to the northwest to join the main San Andreas fault, and lies today at depth beneath Frazier Mountain.

RIDGE BASIN

A great thickness constituting about 11,000 m (36,000 ft) of marine and non-marine clastic sediments was deposited

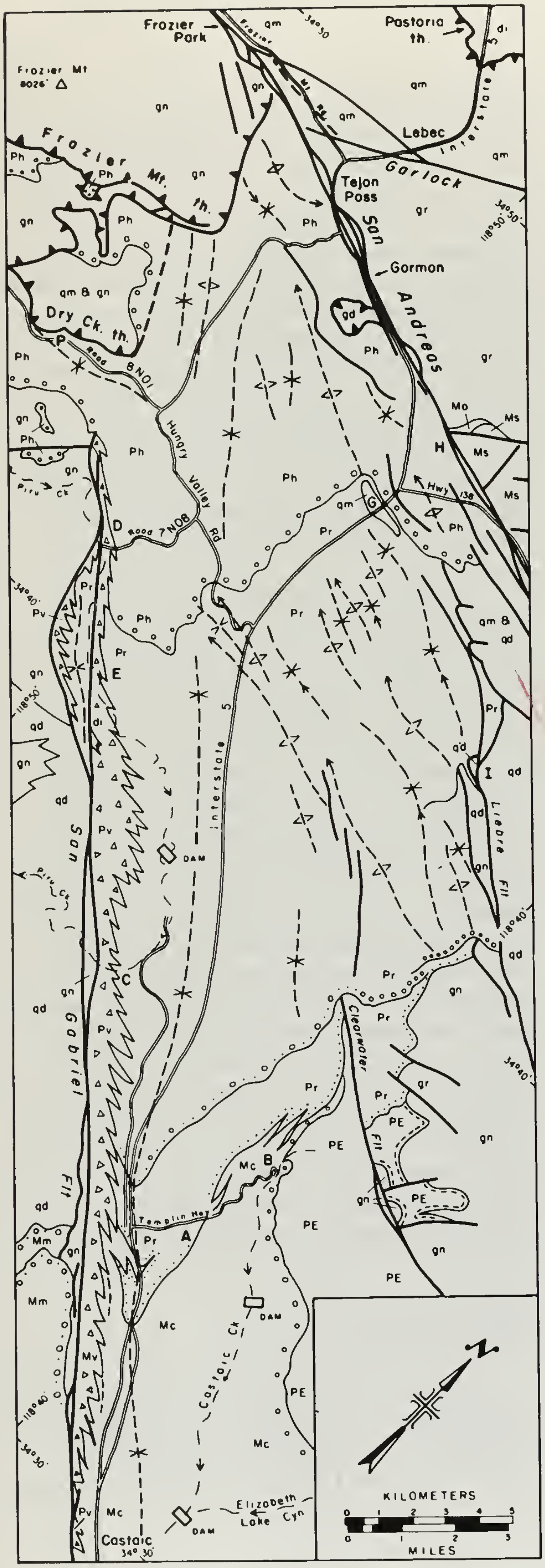

Figure 1. Sketch geologic map of
Ridge Basin area, southern Califc
nia. Symbols: Pre-Tertiary base
ment rocks: gn = gneiss, di = dic
rite, gd = granodiorite, qd =
quartz diorite, qm = quartz monzo
nite, gr = granite; Tertiary rock
PE = Paleocene and Eocene San Fra
cisquito Formation, Ma = Miocene
andesite and related volcanic roc
Ms = Upper Miocene Santa Margarit
Formation, Mc = Upper Miocene Cas
taic Formation, Mm = Upper Miocen
Modelo Formation, Mv and Pv = Upp
Miocene and Pliocene Violin Brecc
Pr = Ridge Basin Group, Ph = Hung
Valley Formation. Quaternary fan
and terrace deposits and alluvium
not shown. Accessible localities
for field trips: A: Templin Hig
way and Old Ridge Route, soft-sed
ment deformation; B: Castaic Can
yon at Templin Highway, unconform
at floor of Ridge Basin; C = Piru
Gorge downstream from Frenchman
Flat, Violin Breccia and San Gabr
fault zone; D = Forest Service Ro
7N08, exposure of San Gabriel faul
zone in cliff (1 km (5/8 mi) to N
from where road crosses Piru Cree
E = at S. end of Forest Service
Road 7N08 along Piru Creek to Buc
Creek, Violin Breccia and facies
changes to finer-grained strata
downstream in gorge; F = Dry Cree
1 km (5/8th mi) north of Forest
Service Road 8N01, Dry Creek thru
shattered veined geneiss above ov
turned Plio-Pleistocene Hungry Val
beds; G = Roadcuts of Interstate
just S of Highway 138 turnoff, fo
ed basement rocks and skidded unc
formity of overlying Hungry Valle
beds, now vertical and disrupted;
H = Gorman Post Road, fault land-
forms along San Andreas fault zon
including scarps of 1857 Fort Tej
Earthquake, sag ponds, exposure o
shattered basement, etc.; I = Old
Ridge Route.

in a long and narrow basin adjacent to the San Gabriel fault during late Miocene and Pliocene times. By Pleistocene time, the basin was filled and later deformation has squeezed and elevated the beds so that they are in view today after deep erosion. The sediments within Ridge Basin grade from conglomerate and sandstone on the northeast to predominately shale along the axis of the trough, and thence southwestward to coarse sedimentary breccia against the San Gabriel fault. Stratigraphic and structural relations (Fig. 2), show that deposition and deformation have gone on hand in hand as the intermontane basin or bolson was filled. Previous works dealing with the Ridge Basin region include Clements (1937), Eaton (1939), and Crowell (1954, 1973a).

Rocks bordering Ridge Basin include both crystalline basement and Tertiary strata. Southwest of the San Gabriel fault Precambrian and younger gneisses (including augen gneiss, blue-quarzt-bearing gneiss, porphyroblastic gneiss, and migmatite) with Mesozoic granite and quartz diorite, lie above the tipped and gently folded Alamo Mountain zone of mylonites and phyllonites (Crowell, 1964, p. 11). Rocks structurally below this tectonic movement zone consist of quartz diorite with bodies of gray gneiss. These underplate rocks, the Alamo Mountain thrust system itself, and the gneissic overthrust plate are all intruded by leuco-quartz monzonite containing biotite dated by K/Ar methods at about 66 m.y. (Evernden and Kistler, 1970, loc. no. 150). Exposed in steep tributaries to Piru Creek near the San Gabriel fault are some tongues of anorthositic diorite not more than a couple of meters thick that are interleaved with blue-quartz-bearing gneiss. Basement southeast of this, and also lying west of the San Gabriel fault zone, consist mainly of quartz diorite and quartz monzonite containing irregular bodies of gneiss. A narrow slice of gneiss occurs within the fault zone, and is interpreted as a segment carried in mainly by strike slip and now intermediate in position between the Tejon and Soledad region. This slice was emplaced when the Upper Miocene Modelo Formation was being deposited as shown by an intra-Modelo unconformity (Figs. 1, 3).

Terrain flanking Ridge Basin on the northeast consists of gray quartz diorite and quartz monzonite with some bodies of gray gneiss within it. Farther south, the gneiss includes elongate bodies of quartzite and marble, presumably representing metamorphosed sediments of unknown age, but probably Paleozoic. This basement terrain is overlain unconformably by Paleocene and Eocene sandstone, shale, and conglomerate assigned to the San Francisquito Formation (Dibblee, 1967, p. 44) and interpreted as part of a moderately deep-sea fan by Sage (1973; this volume). These beds form the floor of Ridge Basin south of the extension of the Clearwater

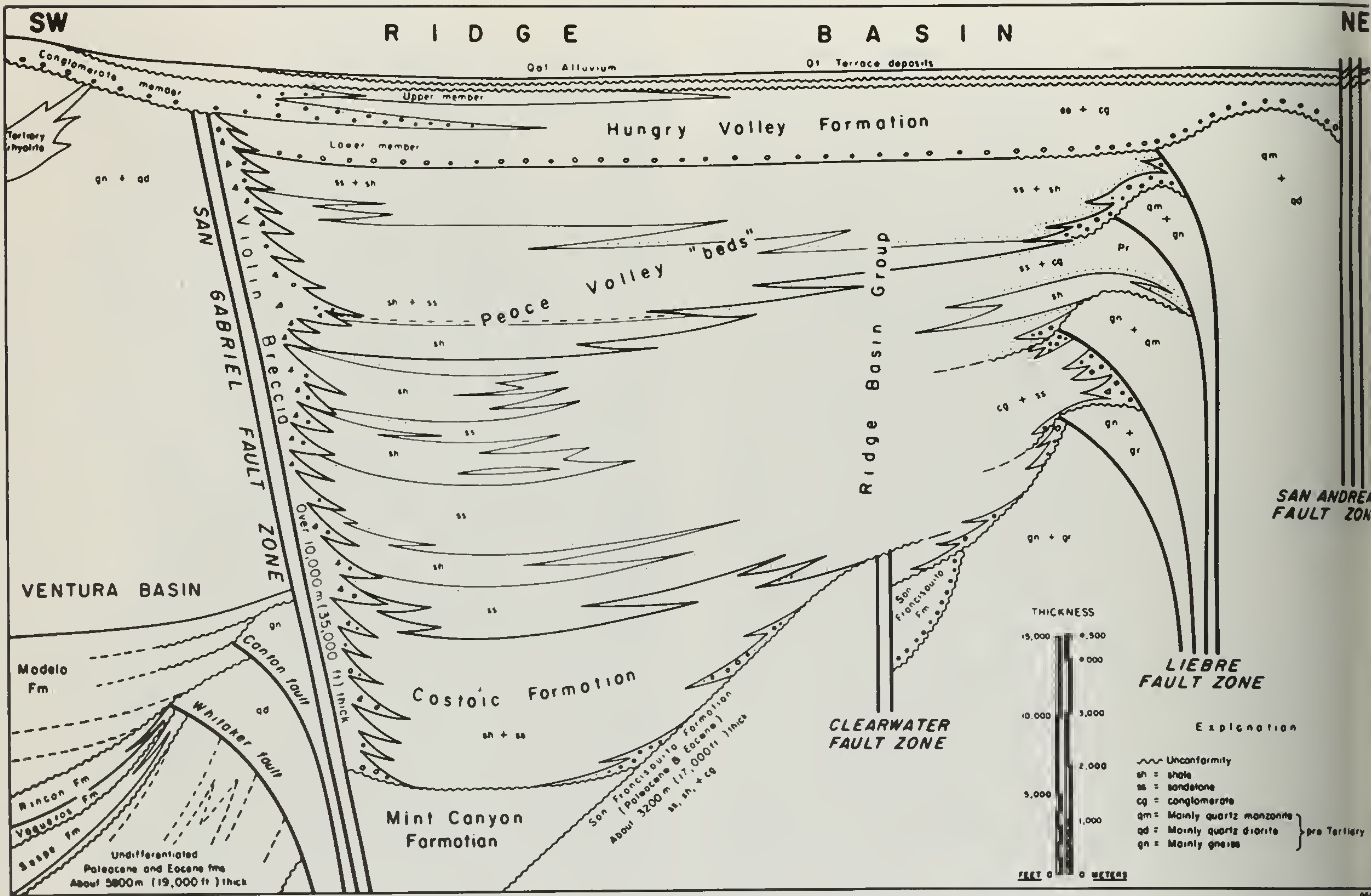

Figure 2. Stratigraphic arrangement, Ridge Basin, southern California. Maximum thicknesses shown approximately to scale; lateral extent is diagrammatic and not to scale.

fault (Fig 2). On the southeast, Ridge Basin strata grade into those of the easternmost beds of the Ventura Basin (Modelo and Castaic formations of the uppermost Miocene) and overlie those of the northwesternmost part of Soledad Basin (Mint Canyon Formation of the middle and upper Miocene). The Modelo and Castaic formations are interpreted as stratigraphic correlatives, displaced by regional trace slip of about 25 or 30 km (15 or 20 mi) on the San Gabriel fault zone in the region of the Castaic Lowlands and through the Honor Rancho Oil Field.

The Ridge Basin Group, about 8800 m (29,000 ft) thick, overlies conformably the marine Castaic Formation, about 2200 m (7000 ft) thick. The lowermost 600 (2000 ft) of the Ridge Basin Group is marine and contains late Miocene mollusks and Foraminifera, but most of the group is nonmarine and was apparently deposited as broad alluvial fans extending basinward into an intermittent freshwater lake. Its age designation, latest Miocene and Pliocene, rests upon its stratigraphic position, on Plio-Pleistocene vertebrate remains in the upper part of the section (Stock, in Crowell, 1950, p. 1638) and on plant and fish remains from the middle part of the section (Axelrod, 1950; David, 1945). Most of the group has been subdivided into lithologic units, as shown on Figure 2, but only the Violin Breccia, lying next to the San Gabriel fault, and the Hungry Valley Formation, topping the section, have been given formal formation names.

The Violin Breccia is an unusual formation in that it is over 10,000 m (35,000 ft) thick stratigraphically but extends along the strike for a maximum distance of only 1500 m (5,000 ft). Throughout its extent it very abruptly grades laterally into finer-grained Ridge Basin strata. The Violin Breccia everywhere consists of a rubble of gneissic blocks up to 2 m (6 ft) in diameter embedded in a sandy and muddy matrix that apparently accumulated as talus or alluvial debris at the base of the San Gabriel fault scarp. Blocks and stones of the Violin Breccia consist of gneisses and other basement types from the Alamo Mountain - Frazier Mountain region on the northwest. Clasts of anorthositic diorite are rare although a slice or landslide mass of this material occurs midway along the outcrop of the breccia (Fig. 1, di; Shepard, 1962). No material from Tertiary beds now lying immediately west of the breccia exposures at its southeastern end, and west of the San Gabriel fault zone, has been noted. The great thickness of the breccia and the long time represented by its accumulation require continuous or frequently intermittent rejuvenation of the fault scarp. Nearly continuous movement must have occurred on the fault zone from some time in the late Miocene until the end of the Pliocene. Moreover, this displacement requires a dip-slip component, down on the northeast into the bolson of Ridge Basin, and up on the southwest to rejuvenate and elevate continuously the same limited source region.

The generalized structure and arrangement of beds within Ridge Basin is shown diagrammatically in Figure 3. Note that successively younger beds lap toward the northeast along the floor of the basin and parallel to the basin axis. A well drilled at A, for example, would penetrate a section not occurring below B. Note that the stratigraphic thickness (a quantity measurable and reproducible in the field) is immense, but that the vertical column of beds laid down at any one place never exceeded about 4500 m (15,000 ft). With respect to the bolson, the locus of sedimentation apparently migrated northwestward with time in order to accomplish this overlapping.

Most of the sediment within Ridge Basin, as judged from facies relations, clast provenances, and structures, came from the north and east. The

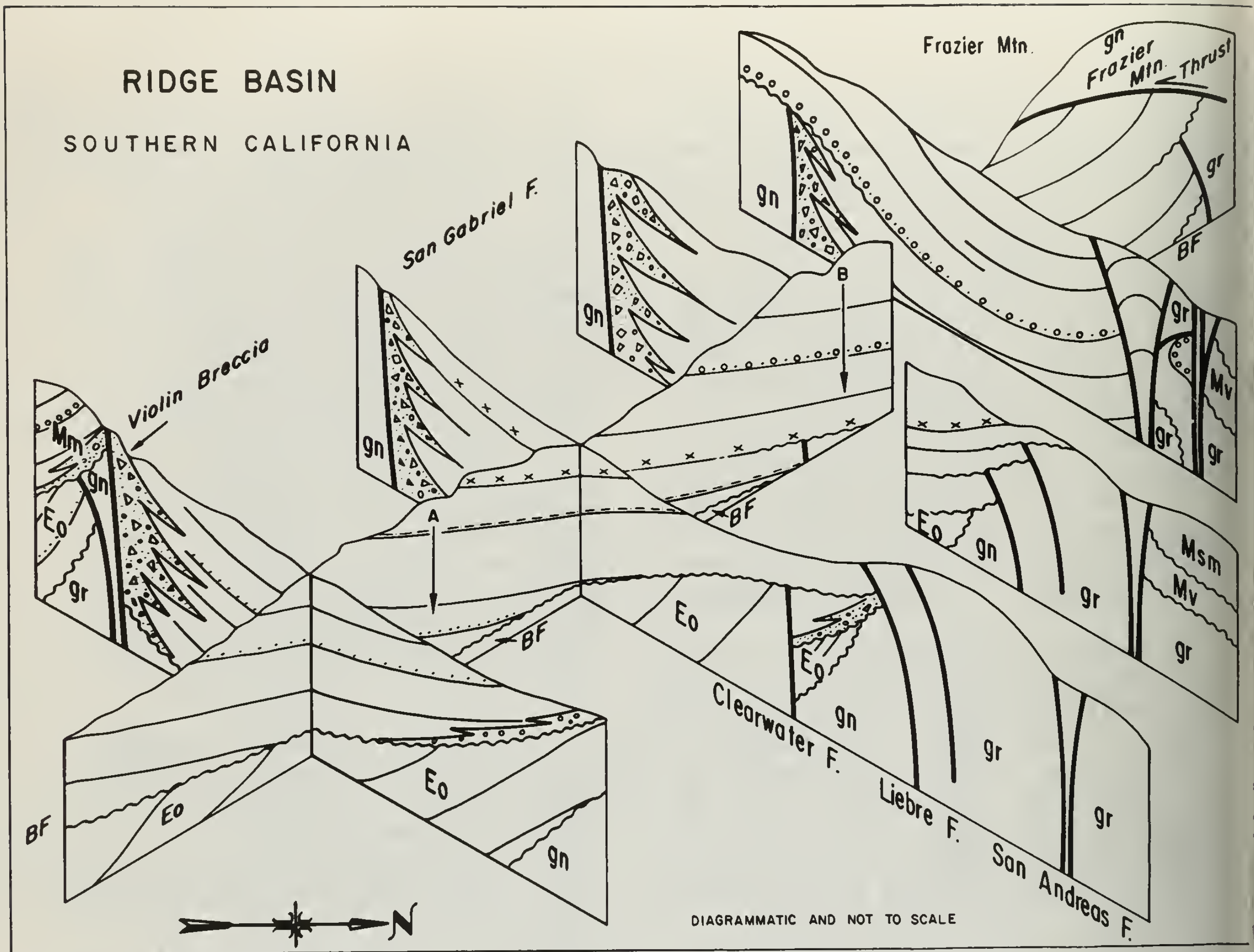

Figure 3. Isometric sketch of Ridge Basin, southern California (diagra- matic and not to scale). Strata of Ridge Basin not labelled. Stratigrp ic section at A is overlapped at B. Symbols: BF = basin floor; gn = gneiss; gr = grantic rocks; Eo = Eocene and Paleocene; Mv = Miocene vol canic rocks: Msm = Upper Miocene Santa Margarita Formation; Mm = Upper Miocene Modelo Formation. Republished with permission of Soc. Econ. Paleontologists and Mineralogists (Crowell, 1974a, Fig. 4).

Violin Breccia, although constituting only a tenth or so of the infilling, nonetheless provides important clues to the way the overlapping beds within Ridge Basin were laid down. Because the source for the debris within the Violin Breccia was a limited and circumscribed area in the vicinity of Frazier Mountain, right slip on the San Gabriel fault is required. This lateral displacement carried newly formed beds away to one side, to make way for the next set on the down-thrown block, and in so doir achieved the overlap. The operat is likened to dumping debris fron a hopper, analagous to the source area, onto a belt moving slowly southeastward, analagous to the bolson floor. By means of tector creep or with successive earthqu on the fault, the bolson moved b downwards and right laterally wit respect to the source area. In s a moving system, the older beds a displaced successively more than younger, so there are innumerabl lues to the fault slip. Both the gnitude and age of slip depend the age of the beds cut at a rticular locality under discus-on. Growth faults such as the n Gabriel do not have unique es nor displacements.

E CONTINUITY OF FAULTING

Within Ridge Basin and its en-rons, and especially on the north-st, there is documentation of ult movement and related defor-tion beginning in the late Mio-ne and continuing to the present me. The evidence comes primar-y from interpretations of the positional history, as described ove, and from unconformities and e cross-cutting of one fault by other. The sketch geologic map ig. 1), simplified here from 24,000-scale mapping completed t still unpublished, shows that ults along the northeastern rder of Ridge Basin ceased their tivity as the basin filled. The earwater fault, for example, dis-aces and deforms a few hundred ters of beds at the bottom of e Ridge Basin sequence in that gion, but the trace of the fault then truncated and overlapped by unger Ridge Basin beds. This gular unconformity is traceable om the point of overlap across e Clearwater fault, to the south d into the center of the Ridge sin sequence where it passes into bedding plane with no discernible conformity. From the center of e trough, the same bedding plane tends into the Violin Breccia and the San Gabriel fault. Similar erlaps occur north of the end of earwater, and involve several her northwest and west-trending ults. Strands of the Liebre ult system, for example, were ccessively overlapped as Ridge sin filled. The base of the ngry Valley Formation corresponds the northeast with one of these overlaps where it crosses over the end of the surface trace of the main Liebre fault. This contact, roughly corresponding to a time marker, trends across the basin and extends into the Violin Breccia, showing that the San Gabriel fault continued to move in its customary style after the Liebre fault had died.

The San Gabriel fault is over-lapped at its northwestern end by beds of the Hungry Valley Formation; these can be followed westward where they lie unconformably upon the bevelled basement terrain. The San Gabriel fault therefore con-tinued displacement on through Pli-ocene time after the Liebre fault ceased movement, a duration of time equivalent to that taken to deposit about 1100 m (3600 ft) of beds. After that, an additional 800 m (2600 ft) or so of fanglomerate was laid down, and these beds were then folded beneath the Dry Creek thrust and other elements of the Frazier Mountain thrust system during mid-Pleistocene time. This thrust sys-tem in turn acquired a slip of at least 4 km (2 1/2 mi) directed relatively toward the southeast (Crowell, 1950, p. 164). After this event, the thrust itself was folded into antiforms and synforms with crustal traces about 540 m (1760 ft) apart and with dips on the flanks of as much as 70 . In turn, splays from the San Andreas fault north-east of Frazier Mountain cross-cut this fault, and neither the San Gabriel nor Frazier Mountain thrust system show evidence of present activity.

Across the northern tip of ridge Basin, and north of the surface trace of the Liebre fault zone, beds of the Hungry Valley Formation are severely deformed and disrupted and in general stand nearly verti-cally. Here as well, fractured and folded basement rocks occur along with splays from the nearby San Andreas fault that have displaced alluvium, terrace deposits, landslide deposits, as well as underlying basement and Hungry Valley beds. Some low-angle thrust faults here, probably moving with oblique slip, have brought basement slabs out across overturned beds of the Hungry Valley Formation.

The source area for the Hungry Valley beds, which lay in the Mojave Desert as judged from stone studies and paleocurrent indicators, has been displaced an unknown distance on the active San Andreas (Crowell, 1973b). Miocene sedimentary and volcanic rocks now lie directly across the fault whereas Hungry Valley debris came from a granitic terrain primarily, with some gneiss, marble, different volcanic rocks, and other rock types.

These relations show that significant movement has taken place on the San Andreas fault here in late Pleistocene and Recent times but it is still unclear to what extent the fault was active concurrently with the San Gabriel fault, or even before. In reconstructing the past tectonic scheme, if the San Gabriel is joined on trend to the San Andreas to the northwest -- a situation that apparently existed before later movements in the region described above -- a gentle or nascent Big Bend probably occupied the Frazier Mountain region. Geologic relations seem to fit with a picture of a pliant crust block, travelling laterally around this bend, that would stretch and sag. At the same time, the block inside of the bend would be squeezed and uplifted (Crowell, 1974a, p. 299; 1974b). Perhaps as the stretching and sagging Ridge Basin block went around the bend, faults within its floor and along its northwestern margin were activated, only to die out later as the lateral movement carried them beyond the place of maximum curvature and maximum strain on the through-going trans form scheme. Such a moving patte fits fault-overlap relations of t Clearwater and Liebre fault syste In time, however, the nascent Big Bend grew to the point where the San Gabriel fault was abandoned a the Frazier Mountain system was born. This thrust system was in turn folded and soon abandoned, and the main movement taken over the presently active San Andreas.

The oldest beds of the Violin Breccia, of late Miocene (Mohnian age, are found at the southeaster end of its occurrence, and are di placed about 30 km (18 mi) from their source area. Across the fault zone now from these beds ar exposures of marine upper Miocene conglomerate of the Modelo Formation, also late Miocene (Mohnian) age. These beds contain facies changes and paleoslope and paleocurrent indicators showing that t formation was deposited from a source area of anorthosite, diori gabbro, gneiss, and granitic rock that lay nearby to the northeast. At present, in that direction, no appropriate basement rocks are ex posed, and all basement is thickl covered with sedimentary rocks of Tertiary age both older and of th same age. With right slip of abo 35 km (22 mi) on the San Gabriel fault, however, the Modelo conglomerates can be placed adjacent to a suitable source area, now exposed in the western San Gabrie Mountains (Crowell, 1952; 1962). This interpretation of the region geology involving right slip of t order through the Castaic-Newhall Lowlands has been quested (e.g. Paschall and Off, 1961), primaril because of the difficulty of trac ing the fault zone through Miocen beds in the subsurface. Below th lowlands, and within the Honor Ra il Field electric-log correlations rd biostratigraphic units show ery little vertical separation. he lithology and provenance of the rata themselves, however, are ery different across the fault Vinterer and Durham, 1962). Displacement through this region appears to have been by regional ace slip primarily, so that the per Miocene units are now juxtaced without much separation.

In recent years data have cumulated on the nature, distriction, and age of the older and asement rocks in both the Tejon as region and in the Soledad sin. As discussed in the introctory article for this guidebook, he total offset of the Tejon tern from that of the Soledad tern is of the order of 60 km (38 i. Moreover, the Mint Canyon rd Caliente formations, because hey both contain the same suite of nglomerate stones (including the istinctive rapakivi-textured artz latite porphyry), were apparrly somehow formerly adjacent, r the middle and late Miocene when hey were deposited (Carman, 1964; hig and Ehlert, 1972). These eds seem to be displaced the same mount as the complex of basement pes and immediately overlying iddle and lower Tertiary beds, and c it follows that all of the right lp is also late Miocene and youngr Southwest of the San Gabriel ault, however, very coarse sedientary breccia older than this ops out in Canton Canyon and is signed to the Sespe Formation (ligocene-Lower Miocene). These eds include huge boulders and ocks of anorthosite and Lowe Granorite, as well as less distinctive rock types, up to 5 m (16 ft) r diameter (Bohannon, this volume). he breccia apparently accumulated t the base of the San Gabriel fault arp to the northeast. If this currence is interpreted in this a, the fault originated in the early Miocene, and is therefore significantly older than late Miocene time, although right slip may not have begun until then. More regional work in detail is needed.

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ECTION 4

ejon Pass to Carrizo Plain

hoto 7. San Andreas fault in Carrizo Plain, looking west toward Soda Lake in the distance. Note offset streams.
J. S. Shelton Photograph No. 2635, 28 June 1959, 3000 ft. elevation.

Photo 8. San Andreas fault zone in Carrizo Plain at Elkhorn Scarp, looking east. Southern tip of Temblor Range in background. Note offset streams and beheaded streams in center of photo.
J. S. Shelton Photograph No. 501, 10 July 1957, 6500 ft. elevation.

E SAN ANDREAS FAULT BETWEEN CARRIZO PLAINS AND TEJON PASS, JTHERN CALIFORNIA

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STRACT

The San Andreas fault at its arp bend in the northern Transrse Ranges separates very differt rock terrains. North of the ult basement rocks consist of anites mainly of Mesozoic age th Sierra Nevada affinities, ntaining included remnants of leozoic metasediments. To the st the basement is composed of ba- metamorphic rocks that may be lifted portions of ancient ocean- crust. The sedimentary section rth of the fault begins with the rine Eocene Tejon Formation and succeeded by a nearly complete quence, including some intercaed volcanic rocks, up into the istocene Series. Many of these thern rock units change facies m continental beds on the east deep-water marine facies on the t where they are sharply truncaed by the San Andreas fault.

Southwest of the fault zone Prebrian gneisses and migmatites, isses of unknown age, and Meso- c granitic rocks of several es are exposed. The Paleocene ocene Pattiway Formation and midtiary nonmarine beds and volic units in the Caliente Range Cuyama Valley area are truncaton the northeast by the San Anras. Mid-Miocene and younger conmerates and sandstones in the thern Transverse Ranges were deited in intermontane valleys ih sources to the northeast. Ass the San Andreas fault in that iection no suitable source areas cur today. Suitable source areas these beds and counterparts to y of the southern basement-rock units have been identified across the San Andreas - San Gabriel fault system in Soledad Basin and the Orocopia - Chocolate Mountain region, indicating about 300 km (180 mi) of right slip.

Emphasis in this paper is upon details observable along the San Andreas fault zone, such as fault landforms, fault slices of many rock varieties, crushed rocks, and upon the striking contrast in rock units across the fault zone as a whole.

INTRODUCTION

In approaching the Transverse Ranges along the San Andreas fault from the northwest, the fault zone curves eastward into the Big Bend, and near Frazier Park has a due east-west strike for a distance of about 6 km (4 mi). The fault then curves gently southeastward across Tejon Pass and continues along the southwestern margin of the Mojave Desert. As the fault enters the Big Bend region south of the Temblor Range its surface trace climbs in elevation and crosses through basement terrain in the Mount Pinos - San Emigdio Mountain - Frazier Mountain region (Figs. 1, 2). The Big Bend region is also notable for the intersection of other major faults with the San Andreas fault: the Garlock, Big Pine, San Gabriel, and Liebre, for example. Despite the conspicuous pattern of the Big Bend region on geologic maps, the evolution and significance of this complex area is still unclear and much additional investigation is needed.

Rock units contrast markedly

across the San Andreas fault zone in this region. Basement rocks as well as overlying sedimentary sections cannot be correlated directly across the fault zone. Some matching sequences have been recognized outside of the Big Bend region and provide evidence for many miles of right slip on the San Andreas fault system, including the San Gabriel fault (Hill and Dibblee, 1953; Crowell, 1962, 1968, this volume; Wiebe, 1970; Ross, 1972; Huffman, 1972; Matthews, 1973).

In the Carrizo Plains area on the northwest sedimentary facies contrast strongly across the fault (Vedder, this volume) and many fault landforms are well displayed (Wallace, 1968; this volume). To the southeast of Tejon Pass, part of the thick sedimentary section within Ridge Basin (Crowell, this volume) is juxtaposed against an eastward-thickening sequence of very different sedimentary and volcanic strata. These units lying north of the fault include the Neenach volcanic rocks and Miocene sedimentary formations (Wiese, 1950; Crowell, 1952; Dibblee, 1967; Matthews, 1973). The fault zone itself through the Big Bend region is marked by scarps, sagponds, offset streams, and other fault landforms lying within a broad, conspicuous fault trough. The trough is primarily the result of long erosion in fault-shattered rocks. This article is primarily concerned with features within and along this fault zone on a route followed by public roads.

ROCK UNITS NORTH OF THE SAN ANDREAS FAULT

Basement rocks within the San Emigdio Mountains and southwestern part of the Tehachapi Mountains consist mainly of gneiss, schist, granitic and gabbroic rocks of several types, and metasedimentary rocks. Part of this strip of basement rocks is composed of quartz monzonite, quartz diorite, and di-rite, and constitutes the upper plate of the north branch of the Garlock fault. This major tecton- movement zone, marked by mylonite and blastomylonite, is exposed in the Neenach Quadrangle (Wiese, 1950; Peters, 1972) and dips to t- north at about 50 degrees. It ov- lies tectonically Pelona Schist, greenschist-facies sequence of pr- bable Mesozoic age reconstituted from graywacke, mudstone, some chert, carbonate rocks, and volca- ic rocks (Ehlig, this volume). A the eastern border of the Lebec Quadrangle, this north-dipping ma- jor fault is truncated by the sou- dipping Pastoria thrust (Crowell, 1952), another major fault. The Pastoria thrust in turn is trunca- on the south by the south branch f the Garlock fault, no doubt the principal strike-slip branch of t- Garlock. Rocks in the upper plat- of the Pastoria thrust, and consti- tuting the long ridge surmounted Tecuya Mountain and Santa Emigdio Mountain, consist mainly of gray granodiorite and quartz monzonite with inclusions of marble and hor- fels. These Paleozoic (?) metasedimentary rocks are best prese- in roof pendants south of the Gar- lock fault; here, the limestone b- have been intruded by coarse pink granite, quartz monzonite, and granodiorite. Basement-rock type cropping out in the westernmost San Emigdio Mountains consist of gabbro, pyroxenite, hornblende qu- diorite, quartz gabbro, amphiboli- and metadiabase (Hammond, 1958; Ross, 1970, 1972). These mafic a- ultramafic rocks may originally h- been of suboceanic origin, wherea- most of the eastern granitic rock north of the San Andreas fault appear similar to those of the so- ern Sierra Nevada. Unfortunately except for local studies, this se- tor of basement rocks has not as been investigated or mapped in detail.

Sedimentary rocks lying unconfor-
ıbly upon this basement terrain
onsist of a thick section of marine
ıd nonmarine beds extending stra-
graphically upward from the Eo-
ne Tejon Formation. On the west,
ds of this Tertiary sequence are
tirely marine up through the Plio-
ne, but, eastward, the section
anges facies rapidly; Oligocene
d Miocene units, for example, are
placed laterally by nonmarine
nglomerates (Nilsen and others,
73). During early and mid-
rtiary times, prisms of sediments
th mainly north-south facies
ends were laid down facing the
a on the west; these beds are now
turned as the result of the ele-
tion of the San Emigdio - Teha-
api Mountains in Pleistocene
me. The outcrop section in map
ew today in the foothills dis-
ays a sequence passing from con-
nental beds on the east into
ep-water marine deposits on the
st (e.g., Hammond, 1958; Nilsen,
73; Nilsen and others, 1973).
ese marine units reach to the
n Andreas fault in the Temblor
nge (Vedder, this volume), and
the northern part of the San
dreas sector described in this
ticle (Fig. 1).

Volcanic rocks in this northern
ctor include Lower Miocene basalt
d porphyritic dacite and Upper
ocene andesite, dacite, and rhyo-
te. The latter rocks, belonging
the Neenach - Pinnacles volcan-
assemblages, occur as slices
thin the fault segment described
rein, and are now found in inter-
diate positions with respect to
eir major outcrop areas in the
nnacles National Monument of the
rthern Gabilan Range, and the
uthern margin of Antelope Valley
uffman, 1972; Matthews, 1973).
is volcanic field has apparently
en sliced through and displaced
out 315 km (195 mi).

ROCK UNITS SOUTH OF THE SAN ANDREAS FAULT

Basement rocks south of the San Andreas fault in the region of the Big Bend consist of various types of gneiss, schist, and granitics. Work by Silver (1971) on lead-uranium isotopes shows that blue-quartz bearing layered gneiss of Frazier Mountain are between 1750 and 1680 m.y. in age, and were intruded by porphyritic granodiorite and quartz monzonite between 1650 and 1680 m.y. ago. The latter rocks, now consisting of distinctive augen gneisses, were metamorphosed about 1425-1450 m.y. ago, and then intruded by gabbro, diorite, and minor anorthosite about 1220 m.y. ago. These definitely Precambiran rocks are best viewed on Frazier Mountain (Fig. 2, locality 23), and along Lockwood and Piru Creeks. Other multiple deformed gneisses, not yet dated isotopically, are well exposed along the roads to the tops of Mt. Abel (Fig. 1, locality 9) and to Mt. Pinos (Fig. 2). Granitic rocks of several types and ages also occur in the region (e.g., Crowell, 1964; Carman, 1964; Lofgren, 1967; Evernden and Kistler, 1970; Ross, 1972). Except for the Pelona Schist lying along the north flank of the Mt. Abel - Mt. Pinos ridge, none of these basement rocks appear similar to those north of the San Andreas fault. On the other hand, many of the distinctive Precambrian rocks are correlated with those of Soledad Basin and the Orocopia Mountains, and are interpreted as displaced by the San Andreas - San Gabriel fault system (Crowell, 1962, this volume).

Sedimentary and volcanic rocks exposed south of the San Andreas fault in the Big Bend region consist of marine Paleogene beds, and of continental mid- and late-Tertiary strata with some intercalated canic rocks. Paleocene and Eocene sandstone and shale (Dibblee, 1973; Carman, 1964; Vedder, this volume; Howell, this volume) are preserved locally. Paleocurrent and provenance studies of the Paleocene strata suggest derivation of these clastic sedimentary rocks from across the fault zone (Sage, 1973, this volume). Mid-Tertiary nonmarine units, with interbedded basalt flows, were deposited in irregular basins now disrupted by subsequent tectonic displacements (Bohannon, this volume). The middle and upper Miocene stratigraphic section in the Caliente Range and Cuyama Valley (Vedder, this volume) thins and changes facies toward the Mt. Abel region, where it is nonmarine (James, 1963; Carman, 1964; Crowell, 1964). The Miocene Caliente and Pliocene Quatal formations were deposited in broad intermontane valleys, and received debris from regions to the northeast across the San Andreas fault, and now offset (Barker, 1972). Conglomerate studies show, for example, that stones in the Caliente Formation are closely related in provenance to those of the Mint Canyon Formation of the Soledad Basin (Carman, 1964; Ehlig and Ehlert, 1972), and that these in turn were probably derived from source areas in the Orocopia-Chocolate Mountains region now northeast of the Salton Sea (Ehlig and others, this volume). Beds of the Quatal Formation can be traced eastward around the south flank of Frazier Mountain into units of the Hungry Valley Formation of the Ridge Basin section (Crowell, 1964, p. 12; this volume). Braod disected Pleistocene fanglomerates, sloping away from higher mountains and lying unconformably on the Quatal and Hungry Valley formations, are conspicuous throughout the region.

SAN ANDREAS FAULT ZONE

Public roads closely follow the San Andreas fault zone from the Carrizo Plains (Wallace, this vo[lume]; Vedder, this volume) to the Tejon Pass region. Landforms resulting from recent faulting, including the 1857 Fort Tejon Earth[quake] (Wood, 1955), are conspicuous (Vedder and Wallace, 1970), as are fault slices of many rock types. Detailed strip maps along this route have been published in Crowell (1964). Localities displaying special features are also described here and shown on Figu[res] 1 and 2 by circled numbers.

BIG PINE FAULT

The Big Pine fault can be followed westsouthwestward from [its] intersection with the San Andreas fault near Lake of the Woods into the Santa Maria Valley, and proba[bly] all the way to the Pacific Ocean (S. C. Comstock, personal comun. 1974). It has had a long and com[plex] history involving dip slip [in] the early Miocene and left slip [of] about 13 km (8 mi) in post-late Miocene time (Hill and Dibblee, [1953]; Poynor, 1960; Crowell, 1962, p. [..]; Carman, 1964; Kahle, 1966; Bohann[on], this volume). Some subdued scarp[s] at places along the fault may be due to Recent displacements; inter[pretations] of these landforms sh[ow], however, that this fault is not [as] active as the San Andreas.

GARLOCK FAULT

From its intersection with the San Andreas fault near Tejon Pass the Garlock fault can be traced eastward for 260 km (160 mi) to [the] Death Valley region. Through the Tehachapi Mountains it follows a linear topographic depression bu[t] landforms within it are subdued a[nd] the result of differential erosi[on] rather than of recent fault acti[vity]. Fresh scarps due to recent fault[ing] are present in the Mojave Desert [to] the east, however (Hill and Dibb[lee]

1953; Smith, 1960; Dibblee, 1967). Offset dike swarms, matching sequences of metasedimentary rocks, and other features in the desert suggest a total left slip on the Garlock fault of about 65 km (40 mi) (Smith, 1962; Smith & Ketner, 1970; Davis and Burchfield, 1973). Because the histories and characteristics of rock units along the Garlock and Big Pine faults are very different it is unlikely that they constitute a conjugate mechanical system (Crowell, 1962; this volume).

OTHER FAULTS

The Abel Mountain - Mt. Pinos block of basement rocks has been uplifted and thrust relatively westward across beds of the Miocene Caliente Formation (Ziony, 1958; Crowell, 1964, p. 14). On the south, this thrust passes into several tear faults with a geometry suggesting that the terrain between the San Andreas and Big Pine faults has been squeezed upward and westward. The San Gabriel fault and Frazier Mountain thrust system are described briefly by Crowell (this volume).

EXCURSION GUIDE

According to their designation on Figures 1 and 2, 32 localities are described briefly below where significant geological features can be observed. For more precise locations, refer to the strip maps in Crowell (1964) or to U.S. Geological Survey quadrangles (Apache Canyon, Ballinger Canyon, Cuddy Valley, Cuyama, Eagle Rest Peak, Frazier Mountain, Lebec, Santiago Creek, and Sawmill Mountain). Distances in miles.

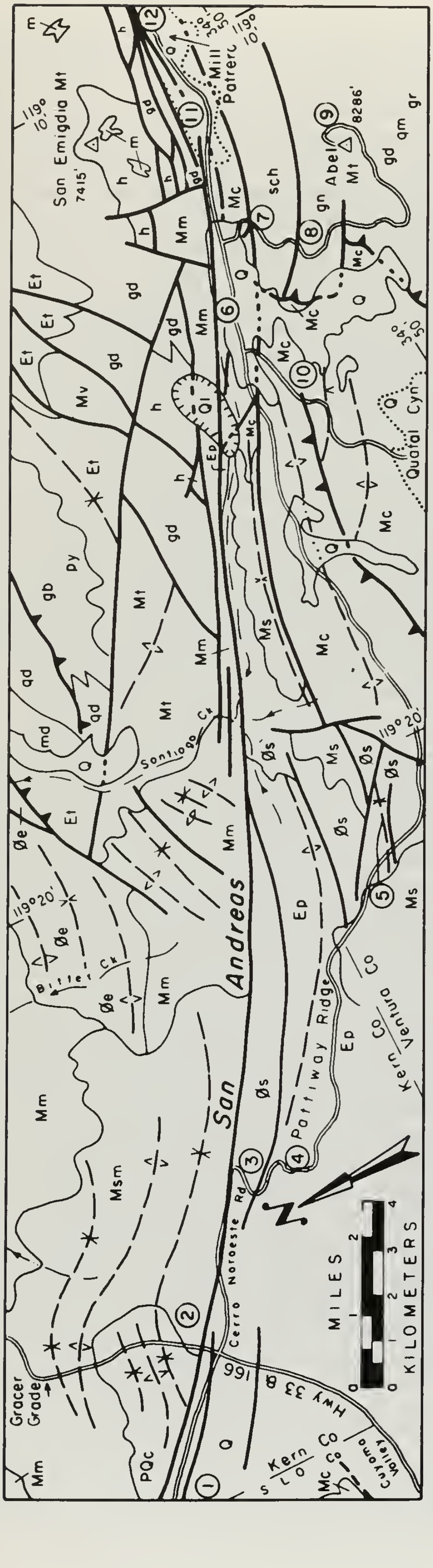
1. (Drive northwestward from Hwy 33 and 166 for about 2 mi on Soda Lake Road from Reyes Service Station). Note fault scarps along the San Andreas fault zone and dry sag pond. Excellent fault landforms are found on to the northwest (Wallace, 1968, this volume). Shattered masses of plutonic and metamorphic rocks, probably slices of basement within the San Andreas fault zone occur on a ridge to the southwest of the road (Vedder, 1970, outcrop marked pKc).

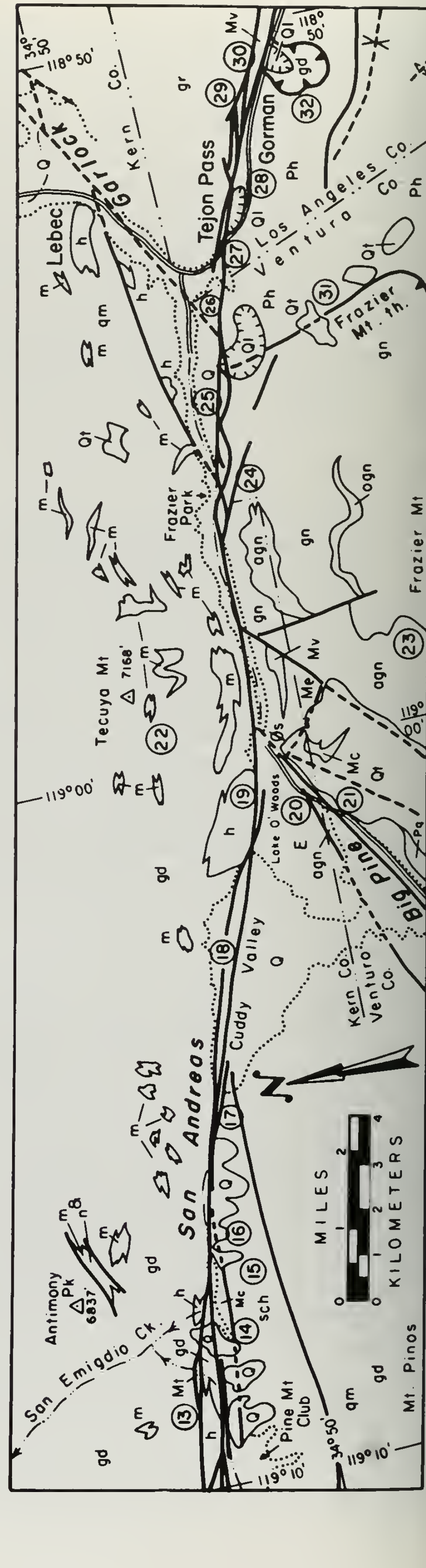
2. (Crossing of San Andreas fault by Hwy 33 and 166, northeast of Reyes Service Station). The San Andreas fault is marked by two narrow fault valleys with a fault ridge (horst) between them.

3. (Cerro Noroeste Road leading to Abel Mountain by way of Pattiway Ridge). Scarps along the San Andreas fault zone face both northeast and southwest; fault traces converge and diverge in map view. Note fault depressions and desiccated sag ponds.

4. (Viewpoint on curve of climbing road, near milepost 5). Views of Cuyama Valley, Caliente Range, Carrizo Plain, and Temblor Range. Trace of San Andreas fault zone clearly visible. Outcrops of Paleocene-Eocene Pattiway Sandstone in roadcuts and on hillsides (Sage, this volume).

5. (Turnout on Cerro Noroeste Road near entrance monument to Los Padres National Forest, about 9.6 mi from Hwy 33 and 166). On the east, deeply dissected terrain along tributaries of Santiago Creek, with trace of San Andreas fault zone prominent. In the roadcut, nonmarine conglomeratic sandstone (buff and reddish) of the Oligocene - Lower Miocene Simmler Formation (Øs) is overlain by marine brown siltstone of the Miocene Soda Lake Formation (Ms) containing yellowish calcareous concretions. Both units dip easterly at about 30 degrees and are overlain unconformably by gravels of the Pliocene Quatal Formation (also called Paso Robles For-


San Emigdio Mt
7415'
Abel Mt
8286'
Mill Potrero
Santiago Ck
Bitter Ck
San Andreas
Pattiway Ridge
Cerro Noroeste Rd
Quatal Cyn
Gracer Grade
Hwy 33 & 166
Kern Co
Ventura Co
MILES
KILOMETERS


Lebec
Garlock
Tejon Pass
Gorman
Los Angeles Co
Ventura Co
Frazier Mt. th.
Frazier Park
Frazier Mt
Tecuya Mt
7168'
Big Pine
Lake O' Woods
Cuddy Valley
San Andreas
Antimony Pk
6837'
San Emigdio Ck
Pine Mt Club
Mt. Pinos
MILES
KILOMETERS

Fgures 1 and 2. Adjoining strip mps from Grocer Grade on Highway 3 and 166 on the northwest to Grman on the southeast. Geology smplified and modified from Cowell (1964). Basement rock smbols: gb = gabbro; py = proxenite; gd = granodiorite; qd = qartz diorite; qm = quartz monzonie; gr = granite; gn = gneiss, an = augen gneiss; m = mainly rble; h = mainly hornfels; md = tadiorite; sch = Pelona Schist. Sdimentary and volcanic rocks: E = Paleocene and Eocene Pattiway Frmation; Et = Eocene Tejon Frmation; E = Eocene formations udifferentiated; Øe = Oligocene Sn Emigdio Formation; Øs = Oligocne - Lower Miocene Simmler Formaton; Mt = Miocene Temblor Formaton; Mm = Miocene Monterey Formaton; Msm = Miocene Santa Margarita Frmation; Ms = Miocene Soda Lake Frmation; Mc = Miocene Caliente Frmation; Mv = Miocene volcanic rcks; Pq = Plio-Pleistocene Quatal Frmation; Ph = Plio-Pleistocene Angry Valley Formation; PQc = Piocene - Quaternary continental dposits; Q = Quaternary deposits, mstly alluvium and terrace debris; Q = Landslides; Qt = Quaternary trraces or high-standing fans.

mtion) that dip westerly at about 3 degrees. Between this locality ad Stop 6 there are excellent vews northwestward and downward ito the imposing canyon eroded by Sntiago Creek. Note the tight sncline paralleling the main San Adreas fault; the fault lies adjcent to it on the north.

6. (Forest Service roads and acess roads to quarries). Catacastic rocks and fault slices withi the San Andreas fault zone. A lrge landslide from the high ridge o the north side of Santiago Canyn has been cut by recent movemnts on the San Andreas fault; the trace of the fault can be followed across its lower third.

7. (Cerro Noroeste Road near turnoff to Camp Condor). Exposures of Miocene Caliente Formation (conglomeratic sandstone) faulted against Pelona Schist.

8. Sharp curve in road and deep roadcut). Pelona Schist faulted against gneiss and migmatite. Some zones of mylonite and blastomylonite in the gouge of this fault zone suggest either recurrent movement or that fault slices of an older fault have been tectonically carried into their present position here.

9. (Summit of Abel Mountain; campground). Exposures of rodded gneiss, migmatized at places and multiply deformed.

10. (Quatal Canyon Road, down canyon from Toad Spring Campground). Reddish schist-bearing sedimentary breccia of Miocene Caliente Formation. Facies changes and clast imbrication show derivation of these sediments from the north; from a source across the San Andreas fault and now disappeared, probably displaced by right slip (Barker, 1972). The breccia interfingers with typical Caliente sandstone and conglomerate along Quatal Canyon.

11 and 12. (Mill Potrero - Pine Mountain Club region). Prominent scarps, offset streams, and other fault landforms along the active San Andreas fault at the base of San Emigdio Mountain, and through part of the Pine Mountain Club development. Note many long fault slices on the steep hillside, including Miocene sedimentary units and plutonic and metamorphic rocks. Groundwater in this region is partly dammed by gouge zones along the fault zone paralleling the road through the valley.

13. (Tributary to San Emigdio Creek). Fault slices of marine Miocene Temblor Formation (sandstone and shale). Slices of hornfels and plutonic rocks.

14. (Continuing eastward along road toward Cuddy Valley). Slices of Miocene Caliente Formation (nonmarine conglomeratic sandstone) south of the active trace of the San Andreas fault and north of a steeply south-dipping fault that has tectonically emplaced Pelona Schist above the sandstone. Fanglomerate deposits from Mt. Pinos slope valleyward, unconformably above the schist, sandstone, and south-dipping fault. These fanglomerate beds are in turn cut by the near-vertical San Andreas fault zone. A main tributary of San Emigdio Creek is sharply offset to the right for nearly a half-mile at Locality 14, near the Jim Whitiner Tree (a giant ponderosa pine, 20 feet in circumference and 142 feet high).

15. (Turnout on road with view down San Emigdio Canyon to the San Joaquin Valley). Prominent thick beds of Eocene and Oligocene sandstone lie unconformably upon basement rocks and form sharp peaks north of Antimony Peak, including Eagle Rest Peak in the Devil's Kitchen area. Old mines on Antimony Peak were worked first by Indians and were examined by W. P. Blake, an early California geologist, in 1857 (Jermain and Ricker, 1949; Troxel and Morton, 1962, p. 56).

16 to 17. (Road follows along hillside above San Emigdio Creek in approaching divide into Cuddy Valley). Road constructed along trace of fault with several sag ponds (mostly dry and alluviated), shutter ridges, and offset streams. Much of the prominent fault topography here is probably the result of the 1857 Fort Tejon Earthquake Road to Mt. Pinos takes off from near divide between San Emigdio Canyon and Cuddy Valley; this is an instructive side trip. Along the road are good exposures, firs of Pelona Schist, and then (to th south) of gneiss and granitic rocks.

18. (Cuddy Valley). Fault scarps, fault-depressed segments, desiccated sagponds, and other fa features. Forest Service roads p vide access to Tecuya Ridge on th north where granodiorite and quar monzonite are exposed along with clusions of marble and hornfels.

19. (Narrows between Cuddy Val ley and Cuddy Canyon). Prominent fault topography and incised drai age arrangement along the San Andreas fault.

20. (Roadcuts west of Lake of Woods settlement). Brecciated au gneiss, that probably occurs as slices within the Big Pine fault zone near its intersection with t San Andreas fault. This rock is similar to that on Frazier Mounta to the south, and to augen gneiss in Soledad Basin and the Orocopia Mountains (Crowell, 1962; this vo ume).

21. (Road to Lockwood Valley an westward). Faint fault scarps al Big Pine fault near Cuddy Ranch, opposite road to Chuchupate Campground and summit of Frazier Moun tain.

22. (Forest Service road to Tecuya Ridge). Paleozoic (?) met sedimentary rocks are preserved a inclusions of marble and hornfels in granodiorite and quartz monzonite.

23. (Road to summit of Frazier Mountain). Gneiss, augen gneiss, and migmatite. Excellent regiona

.w from top.

4. (Frazier Mountain Park., ecially east and southeast of). Fault topography, fault ges, scarps, elongate fault de- ssions and incipient pull-aparts.

5. (On eastward for several es from Frazier Mountain Park). ellent fault landforms along the Andreas, including shutter ges and offset streams.

6. (Gullies beneath terrace de- its). Exposures of basement ks in this region show that the lock fault meets the San Andreas lt at a high angle.

7. Summit of Tejon Pass, at erstate 5 crossing). Slices of ble, hornfels, sheared and minuted granodiorite, granite, rtz monzonite, Miocene andesite, gray conglomeratic sandstone of Plio-Pleistocene Hungry Valley mation (Ridge Basin section), ng with other rock types, occur ween here and Stop 30. The prin- al break of the San Andreas fault marked at the pass by several t of black gouge separating nge Quaternary terrace deposits the north from comminuted and ared granodiorite on the south.

8. (Curve in Interstate 10 be- en summit of Tejon Pass and Gor- town). Large landslide from es to north has slid across the Andreas fault, and then has been placed by later movements on the lt.

9 and 30. (Hillside north of man). Slices of a variety of k units within a locally broad of the San Andreas fault zone. se include rocks similar to those Stop 27 (refer to map, Crowell, 2).

1. Canyons beneath high fans on flank of Frazier Mountain). The Frazier Mountain thrust has emplaced Precambrian gneiss on top of steep- ly dipping Plio-Pleistocene con- glomeratic sandstone beds of the Hungry Valley Formation (Crowell, this volume). The thrust is over- lapped by conspicuous fans high on the mountain slope. These terrace surfaces apparently correlate geo- morphically with the subdued sur- face surmounting the ridge north of Gorman and with remnants between Tecuya Mountain and Lebec.

32. (Hill southeast of Gorman). A large landslide or small thrust plate of broken-up rock, mainly consisting of granodiorite with masses of marble and hornfels in- cluded within it surmounts this hill. The mass presumably slid from a high ridge squeezed up with- in the San Andreas fault zone. Since emplacement, however, the San Andreas has moved again. Young landslides have carried some of this older landslide or thrust debris downslope to the present active San Andreas fault zone along Interstate 5.

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JUXTAPOSED TERTIARY STRATA ALONG THE SAN ANDREAS FAULT IN THE TEMBLOR AND CALIENTE RANGES, CALIFORNIA

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Menlo Park, California

ABSTRACT

Remnants of Tertiary marine basins that formerly transgressed the central segment of the San Andreas fault are preserved in the southern Coast Ranges. On opposite sides of the fault, rocks of the same age contain unlike stratal sequences that record dissimilar paleoenvironments. Reconstructions based upon provenance and depositional patterns suggest post-middle Miocene strike-slip separation of as much as 185 miles (300 km) and post-early Pliocene separation of nearly 50 miles (80 km).

INTRODUCTION

In the southeastern Temblor and Caliente Ranges, late Cenozoic marine and nonmarine sedimentary sequences that are separated by the San Andreas fault represent sharply contrasting basin histories. Comparison of thicknesses, depositional environments, shoreline positions, source terranes and faunal facies across the fault reveal striking mismatches, particularly in rocks of Miocene age. Strata that are now contiguous can be restored to their original position only by large scale strike-slip separation. Although the displaced counterparts of the rock units described lie beyond the limits of the area, they are briefly reviewed because regional palinspastic reconstruction and timing of fault movement are contingent upon inferred amounts of offset.

PALEOGENE

The Pattiway Formation, a marine mudstone, sandstone, and conglomerate unit of Paleocene age (Dibblee, 1973a; Vedder, in press), is exposed in the southeasternmost part of the Caliente Range (Fig. 1). A 3,500-foot (1,070 m) outcrop section (Fig. 2,3), which displays much lenticular and truncated bedding and contains bathyal foraminiferal assemblages, may represent channel deposits of a deep-sea fan. An additional 2,820 feet (860 m) of sandston and shale was penetrated in an explorator well, but it is not known whether these strata are underlain by Upper Cretaceous sedimentary rocks or basement, or both. Directly across the San Andreas fault, however, wells have not penetrated Paleocene beds, and they may not be present there. Along the north side of the San Emigdio Mountains, about 5 to 20 miles (8 to 32 km) southeast of the Temblor Range, basement rocks are overlapped by Eocene strata both at the surface and in the subsurface. In the northern Temblor Range, Paleocene beds that are mostly younger than the Pattiway Formation are exposed, but their extent southward in th subsurface is in dispute (Dibblee, 1973a)

In the southeastern Caliente Range, th type section of the nonmarine Simmler Formation is composed primarily of lenticular variegated beds of mudstone and sandstone with subordinate conglomerate. The formation is unconformable on the Pattiway Formation, and most of the sequence in the type area suggests a flood plain environment with local lacustrine conditions. Elsewhere in the region, particularly in the southeastern La Panza Range and Cuyama Badlands, conglomeratic facies of the Simmler Formation imply deposition in coalescing alluvial fans along an elongate, northwest-oriented basin (Bartow, 1974). The age of the formation is uncertain; it may incorporate strata as old as Eocene and as young as early Miocene, but an Oligocene (?) age generally is accepted. Northeast of the San Andreas fault, opposite the type section of the Simmler Formation, it is inferred that marine strata deeply buried beneath the Temblor Range may be partly equivalent in age to the lower beds in the Simmler; presumably they include the upper beds of the Point of Rocks Sandstone and the Kreyenhagen Shale (H.C. Wagner, J.A. Bartow, and R.L. Pierce, unpub. data). In the northwestern Temblor Range, the Point of Rocks Sandstone probably represents bathyal fan deposition in a late Eocene sequence

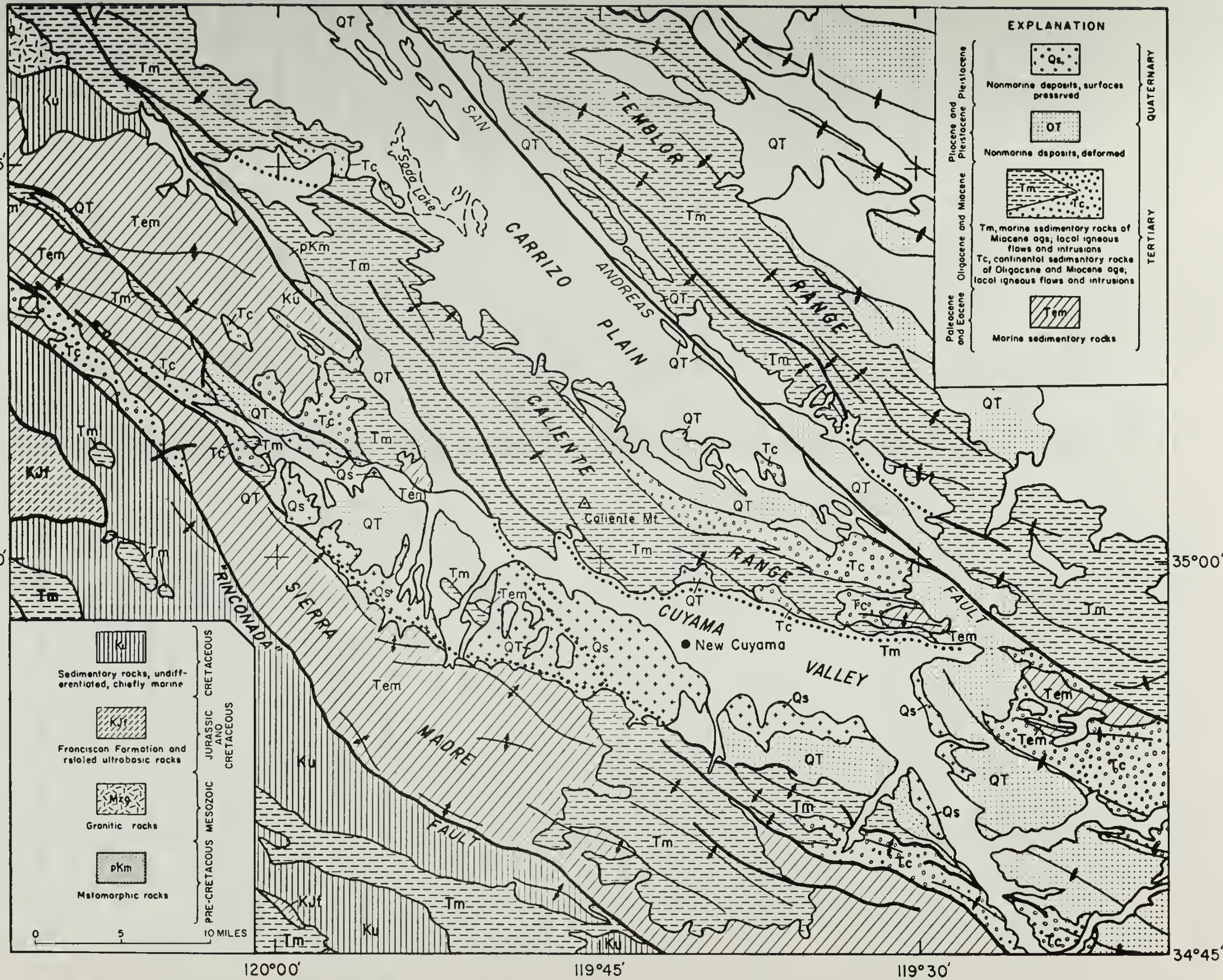


Figure 1. Generalized geologic map illustrating distribution of composite rock units and major structures in the eastern part of the southernmost Coast Ranges. Modified from Vedder (1973).

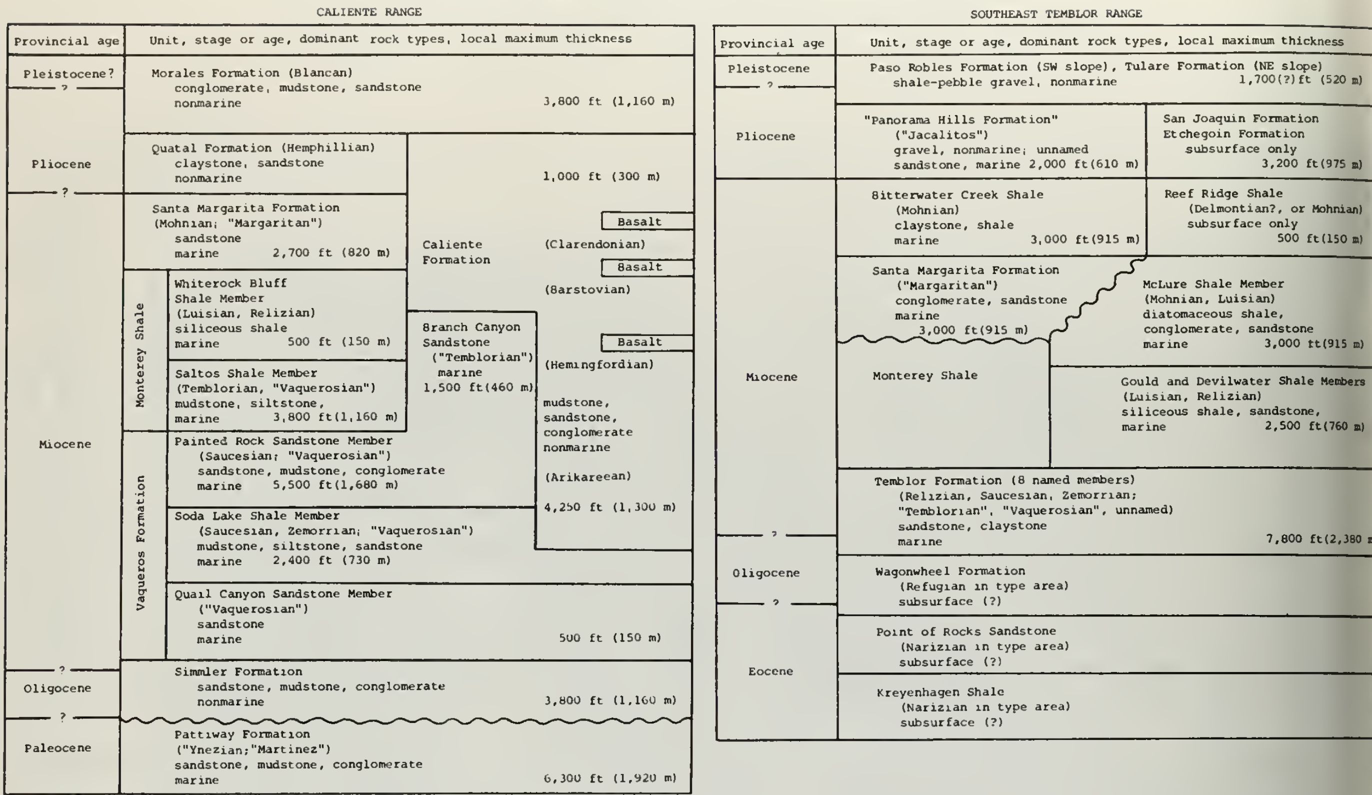


Figure 2. Chart of Cenozoic stratigraphic units in the Caliente and Temblor Ranges. Stage names are applicable only to marine units that contain representative faunas.

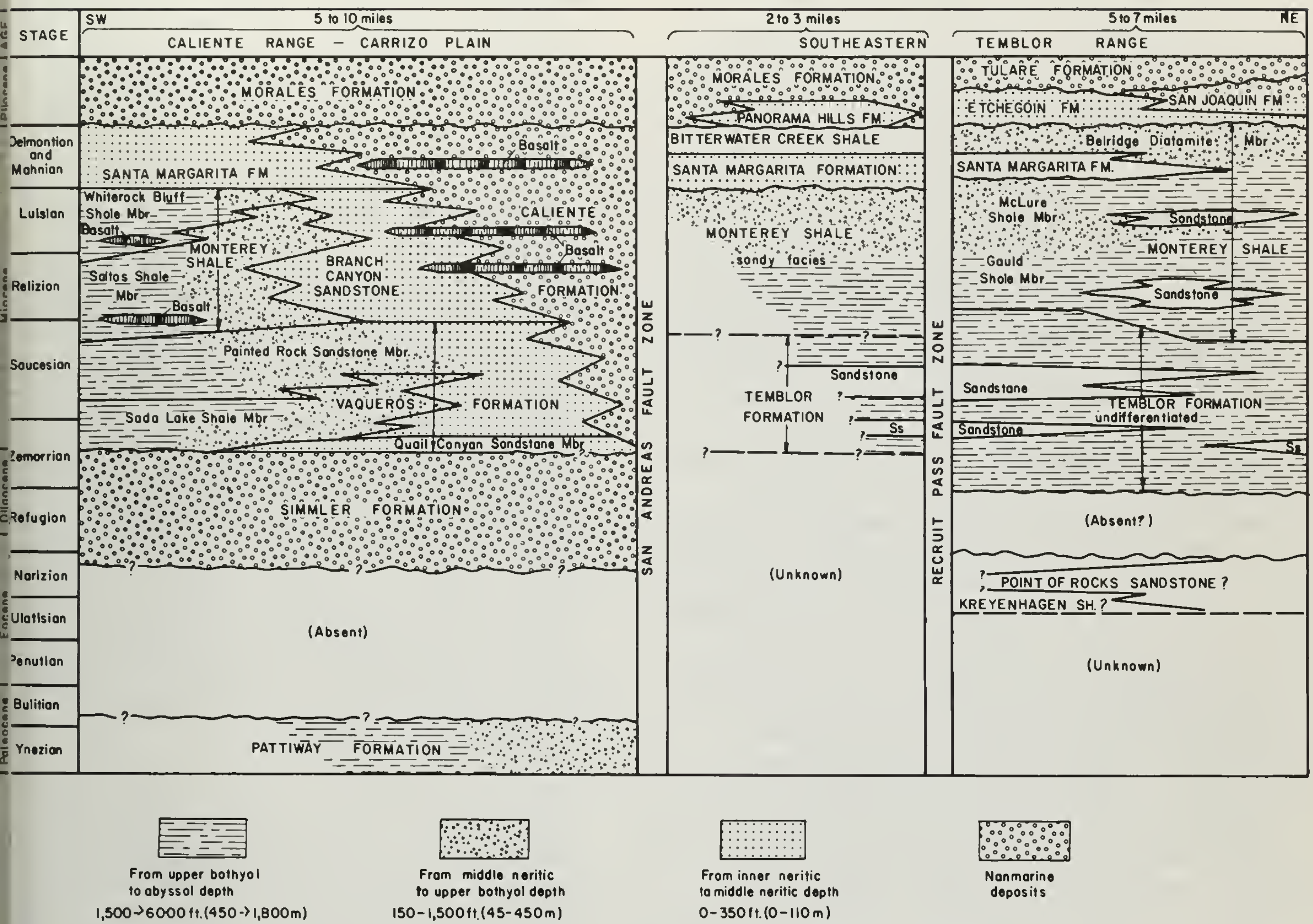
that may have been displaced about 200 miles (320 km) from similar rocks in the Santa Cruz basin (Clarke and Nilsen, 1973). Foraminiferal assemblages from the Kreyenhagen in the northern part of the Temblor Range suggest a late Eocene age (Narizian) and deposition at depths that include most of the bathyal zone (R.L. Pierce, written commun., 1970). Oligocene (Refugian and lower Zemorrian) strata have not been penetrated by wells in the southeastern Temblor Range, but they may be present at greater depth, inasmuch as rocks of this age occur in adjoining areas both to the northwest and southeast. Equivalent rocks to the northwest represent bathyal to abyssal marine environments, and Lamb and Hickernell (1972) report bathyal marine Oligocene strata in a well about 5 miles (8 km) southeast of the Temblor Range. Offset counterparts of the nonmarine Simmler Formation have not been identified, but possibly correlative strata occur in the Soledad basin east of the San Gabriel fault and at Cajon Pass east of the San Andreas fault (Bartow, 1974).

NEOGENE

Rocks of Miocene age are widely distributed in both the surface and subsurface sections on both sides of the San Andreas fault in the southern Coast Ranges, but the depositional environments in the southeastern Temblor Range are strikingly different from those of strata of the same age on the opposite side of the fault in the southeastern Caliente Range. For convenience of description, these successions are divided chronologically into early, middle, and late, following the usage of Addicott (1972), Savage and Barnes (1972), and Vedder (1973).

Early Miocene strata

Along the southwest edge of the San Joaquin Valley in and adjacent to the Temblor Range near Taft, interbedded sandstone and shale units of early Miocene age are as thick as 6,000 feet (1,830 m). Microfaunal assemblages indicative of middle and lower bathyal depths suggest that these beds are



ure 3. Schematic stratigraphic diagram showing contrast in rock units and eobathymetry across the San Andreas fault zone.

bable correlatives of the Santos Shale r Agua Sandstone Members of the type blor Formation farther north (R.L. Pierce, tten commun., 1970). West of the fault the Caliente Range, as much as 10,000 t (3,050 m) of interbedded sandstone and lystone of the same age is exposed in the inity of Caliente Mountain, where these cks are assigned to the Vaqueros Formain. The basin axis in which these beds cumulated is 5 to 10 miles (8 to 16 km) t of the fault; from there the sandstonelystone section thins and coarsens toward fault and intertongues eastward into marine beds (Fig. 3). From bottom to , the subformational units involved are bathyal Soda Lake Shale Member of the ueros Formation in its type area, the llow-marine lower part of the Painted Rock Sandstone Member in the southeastern part of the range, and the lowermost part of the nonmarine Caliente Formation.

Offset counterparts of these early Miocene strata are not known with certainty. On the west side of the fault, more than 200 miles (320 km) to the northwest, as much as 6,000 feet (1,830 m) of marine strata, predominantly of deepwater aspect, occur in the Santa Cruz basin and formerly may have been contiguous to the southern Temblor Range section (Addicott, 1968). Early Miocene marine and nonmarine conglomeratic sandstone beds near Cajon Pass may be equivalent to the nearshore parts of the Caliente Range sequence (Bartow, 1974). Ehlig (1973) suggests that correlative nonmarine strata in the Soledad basin have been displaced 35 to 40 miles (55 to 65 km) from the Cuyama Badlands by post-early Miocene right-slip movement along the San Gabriel fault system, an additional 135 miles (215 km) on the San Andreas fault, and 15 miles (24 km) on the San Jacinto fault.

Middle Miocene strata

The microfaunal content of the shaly beds in the upper part of the Temblor Formation and lower part of the Monterey Shale in the southeastern Temblor Range indicates that the bulk of the middle Miocene section there was deposited in lower bathyal depths (Fig. 3). Directly across the fault beneath the Carrizo Plain and in the Caliente Range, correlative nonmarine beds in the middle part of the Caliente Formation grade successively westward into the Branch Canyon Sandstone and Saltos Shale Member of the Monterey Shale, deposited in neritic and bathyal environments (Fig. 3). This oscillatory shoreline trended north to northwest (Clifton, 1968), and the maximum amount of marine sedimentation probably occurred in a subsiding trough 7 to 10 miles (11 to 16 km) west of the fault. In the same area, one of the several basalt flows, which seem to be restricted to the west side of the fault, shows evidence of having flowed to the west-southwest across the shoreline (Clifton, 1967).

A discontinuous depositional trough that seems to correspond to the truncated deep-water section of middle Miocene age in the Temblor Range occurs west of the fault from the Gabilan Range north to Point Reyes, but the stratigraphic sequence there is thinner and the correlation is not definitive. Nevertheless, the widths of these truncated belts are comparable. The southern margins are now separated by a minimum distance of about 130 miles (210 km), possibly as much as 180 miles (290 km) (Addicott, 1968, Fig. 4). Dislocated equivalents of the middle Miocene nonmarine su-cession within the middle part of the Caliente Formation directly west of the fault have not been conclusively identified east of the fault, but possible source terranes for equivalent strata in the Cuyama Badlands have been noted east of the Salton Sea by Ehlig (1973) that would require a cumulative slip of approximately 185 mil (300 km) across the San Andreas fault system.

Late Miocene strata

On the eastern flank of the south-eastern Temblor Range, as much as 6,500 feet (1,980 m) of marine claystone and shale in the Monterey Shale form the lat Miocene succession. Closer to the fault along the western edge of the range, a middle Miocene shale and sandstone secti is unconformably overlain by late Miocen breccia and sandstone beds that suggest high energy, shallow-water environment. These coarse clastics, which are assigne to the Santa Margarita Formation, coarse and thicken progressively westward but wedge out eastward into diatomite and shale units within the upper part of the Monterey Shale (Fig. 3). These lens of pebble to boulder size granite, rhyolite, and schist detritus are mappab for nearly 25 miles (40 km) along the we edge of the southeastern Temblor Range a presumably were derived from a precipito coastal zone directly to the west. The boulder beds of the Santa Margarita Formation are succeeded conformably by a la Miocene lower bathyal to abyssal diatomaceous claystone unit, the Bitterwater Creek Shale (Vedder, 1970; Dibblee, 1973 On the opposite side of the fault in the southeastern Caliente Range, arkosic flo plain deposits in the late Barstovian an early Clarendonian part of the Caliente Formation probably grade westward into littoral marine sediments of the Santa Margarita Formation west and northwest c Caliente Mountain (Fig. 3), but the relations are obscured by overlapping Quaternary beds along the Carrizo Plain. The late Miocene nonmarine beds progressively coarsen and thicken toward the fault, and paleocurrent features indicate transport from east to west (Clifton, 1968).

The most likely sources for the brecc

the Temblor Range are the crystalline
sement and volcanic rocks in the Gabilan
nge about 150 miles (240 km) to the
rthwest (Fletcher, 1967; Huffman, 1972).
ssible counterparts of the late Miocene
aly section in the Temblor Range occur
the west side of the fault in the sub-
rface section near the southern part of
e Gabilan Range, where the maximum
ickness of the shale unit is comparable
t the sediments represent a shallower
cies than those in the southeastern
nblor Range (Addicott, 1968). These
ations suggest a separation of about
0 miles (160 km). East of the fault,
ther equivalent strata nor a source
rane have been identified that seem to
closely related to the late Miocene
nmarine section in the Caliente Range.
ssible lithogenetically equivalent strata
present in the Ridge basin and Soledad
in area between the San Andreas and
Gabriel faults. A unique source for
granitic detritus in the upper part of
Caliente Formation remains unidentified.

locene strata

Bordering the east side of the fault,
ng the west side of the Temblor Range
in the Panorama Hills, marine mudstone
sandstone beds of probable early
locene age extend as discontinuous out-
rps for approximately 7 miles (11 km)
allel to the fault. These strata are
nonformable on the Bitterwater Creek
hle and wedge out northward into non-
ine gravels that are assigned to the
ales Formation by Dibblee (1973a,b).
s marine unit, which formerly was in-
lded in Dibblee's (1962) Panorama Hills
mation (Fig. 3), probably is less than
,00 feet (330 m) thick. The clastic
tent and fossil mollusks in the marine
es suggest that they were derived in part
m Miocene sedimentary rocks directly to
east and were deposited at neritic
ths. On the opposite side of the fault,
re is no known marine Pliocene section
oughout the Carrizo Plain-Caliente
ge region. Partly correlative nonmarine
tata in the uppermost part of the Caliente
mation, the Quatal Formation, and the
ales Formation along the northeast edge
of the Caliente Range represent flood
plain and lacustrine conditions in late
Clarendonian, Hemphillian, and early
Blancan time (Repenning and Vedder, 1961).
Of these nonmarine units, only the locally
derived Morales Formation is mapped east
of the San Andreas fault (Dibblee, 1973b).
The nearest marine strata on the west
side of the fault that may be the offset
equivalents of the Pliocene beds in the
Panorama Hills are about 1,500 feet (460
m) thick in exploratory wells near
Shandon about 50 miles (80 km) to the
northwest (H.C. Wagner, J.A. Bartow, and
R.L. Pierce, unpub. data).

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THE SAN ANDREAS FAULT IN THE CARRIZO PLAIN-TEMBLOR RANGE REGION, CALIFORNIA

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TRACT

Geomorphic features characteristic of e San Andreas fault zone are excep- nally well displayed in the Carrizo ain-Temblor Range region, California. fset stream channels, elongate grabens, gs, and linear ridges are among the ult-related features found in the area. a result of movement on the San dreas fault during the earthquake of 57, many stream channels were offset, e by as much as 10-11 m. One estimate the recurrence interval between earth- kes as large as that of 1857 is about 0 years.

RODUCTION

Many geomorphic features associated ih the San Andreas fault are class- cally displayed along a segment of the ult from about 100 to 200 km (60-120 i northwest of Los Angeles. There, ween the Temblor and Caliente Ranges, h fault passes through an arid region nwhich most landforms are unobscured yvegetation.

Bordering the fault on the southeast san area of low relief known as the arizo Plain. Soda Lake, an ephemeral, aine lake, lies in a low, undrained at of the plain. To the northeast are eries of hills, including the Elkhorn n Panorama Hills, that might be con- iered the western flank or foothills fthe Temblor Range.

The boundary between the hills and lins broadly marks the trace of the a Andreas fault zone, but the most tiking geomorphic expressions of ividual fault strands generally are iear troughs, valleys, gulches, and crplets, just within the southwest lnks of the hills, or crossing parts fthe Carrizo Plain near or between the hills. Many of the valleys and gulches are erosional features, formed by the action of intermittent streams that flow from the Temblor Range to the fault where they are deflected and cut channels in the more easily eroded brecciated and disturbed rocks along the fault. Some patterns of channels are more a result of right-lateral slip along the fault than of differential erosion alone. Among the characteristics and patterns formed by these processes are offset or beheaded channels, "Z"-shaped channels, deflected drainage and trellis drainage, warped or curved drainage, and en echelon channels (see Fig. 2).

Many geomorphic features result chiefly from differential uplift or depression, block tilting or warping, or lateral differential movement. Among these features of primarily tectonic origin are elongate grabens or troughs, sag ponds, linear scarplets and ridges, tilted and rotated blocks, shutter ridges, medial ridges, en echelon lineaments, and fold ridges.

ROCKS ALONG THE FAULT

The San Andreas fault divides the region into very dissimilar blocks of basement rocks and overlying sedimentary sequences (Dibblee, 1973a; Addicott, 1968). Large-scale (tens or hundreds of kilometres) strike slip in a right-lateral sense has juxtaposed these dissimilar blocks. Some of the evidence and arguments for this large slip are reviewed by J. G. Vedder in a companion paper in this volume.

The dominant rock units exposed at the surface, within a kilometre or so of the fault trace, are relatively young geologically, including Pliocene, Pleistocene, and Holocene sediments (see Vedder, 1970; Dibblee, 1973a, 1973b).

Most of these deposits are nonmarine gravel, sand, and silt derived locally from the Temblor Range. They are poorly to moderately indurated. At a few places rocks as old as Miocene are exposed near the fault.

The Morales Formation, of Pliocene age, and Paso Robles Formation, of Pliocene(?) and Pleistocene age, are extensively exposed in the Panorama Hills. In the Elkhorn Hills the Paso Robles Formation forms more than 90 percent of the outcrops. Alluvium and terrace deposits of several ages can be recognized, as well as numerous landslide deposits.

OFFSET AND DEFLECTED STREAMS

One of the most convincing lines of evidence for right-lateral strike slip on the San Andreas fault is that based on offset stream channels. These are nowhere better displayed than in the Carrizo Plain area. Arnold and Johnson (1910), Willis (1925), and Wood and Buwalda (1931) described some of these features. Wallace (1968) found more than 130 channels between Cholame and Camp Dix that appeared to display true offset by right-lateral slip, a few by more than 1,000 m.

Many channels are offset by 7 to 14 a particularly common offset is between 10 and 11 m (see Wallace, 1968). Some of the small channels offset by 10-11 m appear to have been displaced by a sing episode of movement and thus may represent displacement related to the 1857 earthquake. Figure 1, for example, sho two small channels that slope toward th viewer. The trace of the San Andreas fault bisects the frame from left to right. The channel at the left is beheaded at the fault trace at the uphi edge of the clump of vegetation in the channel. Presumably the uphill segment of the channel at the right was originally the headwaters of the channel at the left. The microgeomorphology between the two channels suggests no period of intermediate offset during which intermediate channels or bends of channels were carved. Rather, the terrain suggests one sudden offset of between 10 and 11 m. This set of channels is one of several good example of offset channels in sec. 11, T. 32 S.

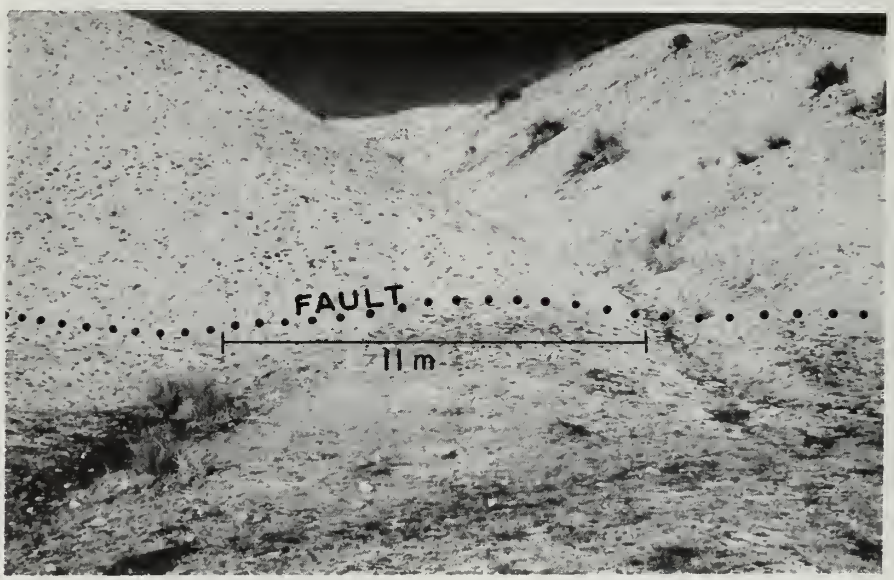

Figure 1. Channel at left (note dark vegetation) may have been displaced in 1857 about 11 m from the channel at right.

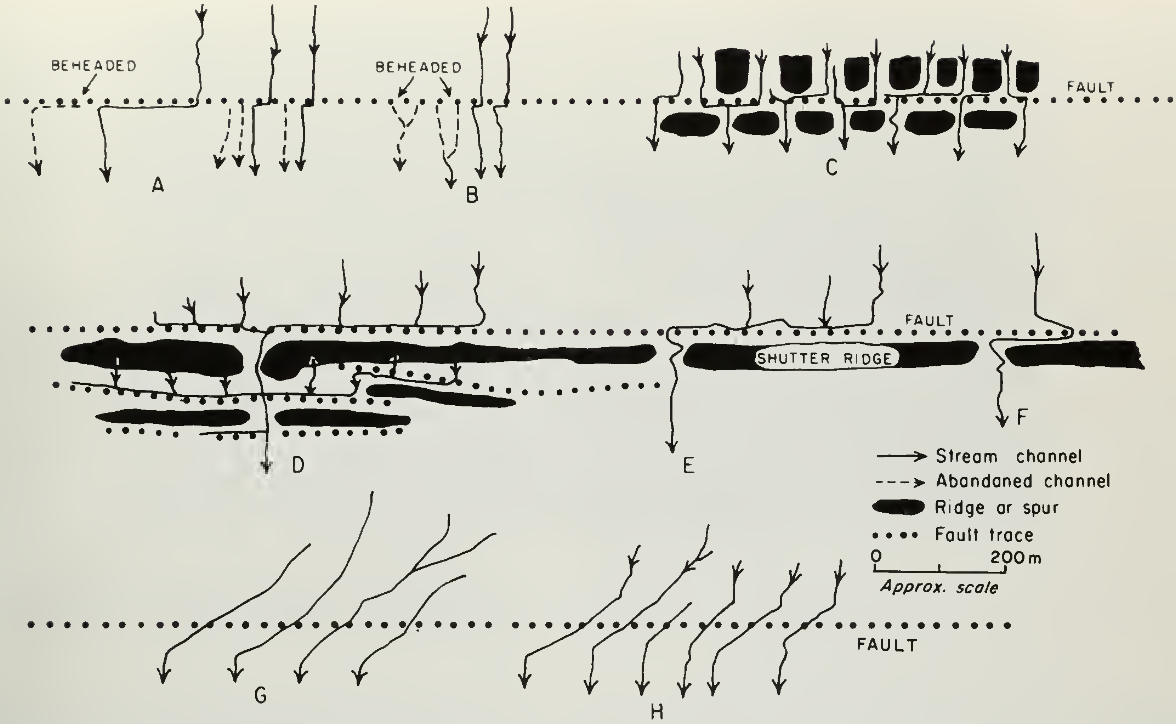

Figure 2. Diagrammatic representation of patterns of fault-related stream channels found in the Carrizo Plain area.

OFFSET CHANNELS

A. Misalinement of single channels directly related to amount of fault displacement and age of channel. No ridge on downslope side fault. Beheading common.
B. Paired stream channels misalined.

COMBINATION OF OFFSET AND DEFLECTION

C. Compound offsets of ridge spurs, and offset and deflection of channels. Both right and left deflection.
D. Trellis drainage produced by multiple fault strands, sliver ridges, and shutter ridges.
E. Offset plus deflection by shutter ridge may produce exaggerated or reversed apparent offset.
F. Capture by adjacent channel followed by right-lateral slip may produce "Z" pattern.

FALSE OFFSETS

G. Differential uplift may deflect streams to produce false offset.
H. En echelon fractures over fault zone followed by subsequent streams produce false offset.

R. 21 E., in the Panorama Hills quadrangle. Each offset or deflected channel system presents a different microgeomorphologic problem, no two of which are identical. Wallace (1968, p. 10) noted that stream channels of small or intermediate size (100-500 m long) best record displacements of a few metres, whereas longer stream channels best record larger displacements.

The factor that probably complicates the drainage patterns most drastically and makes interpretation difficult is vertical tectonic movement. Uplift of only a few centimetres of the block under the downslope segment of a stream may be enough to deflect a small stream, and if a linear block along the fault is raised by as much as several metres across the general drainage pattern, large deflections, both right or left lateral, can result. Figure 2 diagrammatically illustrates some characteristic situations; most are represented in the Carrizo Plain area.

Some left-lateral channel offsets are recorded that are as yet unexplained by deflection, and it should be kept in mind that local left-lateral slip is possible within an overall right-lateral strain field. For example, a thrust or differentially folded block might be bounded by left-lateral slip on one side and right-lateral slip on the other.

VERTICAL DISPLACEMENTS

Inasmuch as the San Andreas fault is characterized by tens, and possibly even hundreds, of kilometres of strike slip, it should not seem surprising that local blocks a few kilometres or less on a side are jostled differentially along the fault and move either up or down by as much as a kilometre or more during the active life of the fault. The ratio of vertical to horizontal movement may be about 1 to 10 or 1 to 20. On a small scale, for example, scarplets up to a metre or so high seem fresh enough to be related to the 1857 event in which 10 m of right-lateral slip probably occurred. As one walks along the most recently active trace, one can find alternately scarps facing southwest and northeast. Apparently block movement or buckling differentially raised or depressed adjacent areas.

Sags (or "sag ponds" if filled with water) are very common and result where irregularities in the fault trace create local tension and collapse of blocks between branches or strands of the fault. Sags generally are a few hundred metres long and a few metres to tens of metres wide. They may lie from a fraction of a metre to several metres below the surrounding terrain. Elongate grabens similarly are depressed blocks between parallel branches of the fault (Fig. 3).

The Elkhorn Hills are an elongate upwarp, the crest of which is broken into a series of grabens. Some of the grabens have a sigmoid pattern (see Fig. 4), suggestive of broad strike-slip strain. The upwarp may have formed when gouge and brecciated material in a fault zone approximately 2 km wide was squeezed upward in a semi-plastic state by regional stresses normal to the fault zone. The overlying, poorly consolidated, Paso Robles Formation, once upraised, has slid laterally, producing large areas of landslides on the flanks of the upwarp and grabens at the crest. The grabens were later bowed by right-lateral strain into the sigmoid patterns now present. Large landslide blocks moved southwest, crossed the most active strand of the San Andreas fault, and were then transported northwestward from their original position. The elongate block "A" (Fig. 4) may be such a transported landslide block.

SEISMICITY AND FAULT MOVEMENT

This segment of the San Andreas fault is seismically very quiet at present (Brune and Allen, 1967), although the great earthquake of 1857 probably had a magnitude greater than 8. Fault offset

Figure 3. Elongate graben along San Andreas fault.

Figure 4. Grabens at crest of Elkhorn Hills. Note sigmoid pattern of some. Block "A" may be landslide block moved laterally from "B."

during the 1857 earthquake was not accurately recorded, but a circular corral, described by Wood (1955), was offset to produce an "S" shape and clearly demonstrated right-lateral slip of several metres. Numerous small stream channels display offsets of from 7 to 15 m (Wallace, 1968) and warrant the assumption that fault displacements in this range probably occurred in 1857.

Geodimeter measurements made during the period 1959 to 1973 (Savage and others, 1973) indicate very small strain rates. One geodimeter line, trending north-south about 30 km and crossing the fault due west of Taft, shows no appreciable change in length between 1959 and 1973. Examination of fences up to 50 years old that cross the fault revealed no measurable misalinement (Brown and Wallace, 1968).

The amount of displacement of distinctive geologic units suggests offset rates in the range of 1.4 to 2.1 cm per year for the past 10 to 20 million years (Clarke and Nilsen, 1973; Grantz and Dickinson, 1968). The contrast between the long-term rate and the slow or negligible movement in the past few decades has led some workers to describe this segment of the fault as being locked. "Locked," in this sense, conveys the interpretation that elastic strain continues to build up uniformly at a rate equivalent to the long-term offset rate, but that for some reason this segment of the fault is unable to slip and accommodate the elastic strain at present. Rupture can be expected at some time in the future when the strength of the lock is exceeded.

Tectonic slip or "creep," although unknown in this segment of the fault, characterizes the segment to the northwest from Cholame to San Juan Bautista. There, in a few places, measured creep rates very nearly match the long-term offset rate of geologic units, although over much of the segment creep rates are less than 1 cm per year.

EARTHQUAKE RECURRENCE

Repeatedly the question arises, "How often will a great earthquake occur?" One approach to an answer for this segment of the fault is to compare the approximately 10 m of offset that possibly accompanied the 1857 earthquake with the long-term geologic rate of mov ment of approximately 2 cm per year. A a constant rate of 2 cm per year of elastic strain buildup, 500 years would elapse before the potential for 10 m offset was accumulated. At the rate of 1.4 cm per year, approximately 700 year of accumulation would be required.

Another approach is based on countin small earthquakes that occur often enough for statistical comparisons of numbers of earthquakes at several magnitudes. On a logarithmic graph, the magnitude-census relation plots approxi mately as a straight line, the slope is expressed as a "b" value, and extrapola tion to large infrequent earthquakes is believed to give a useful evaluation of recurrence. An estimate by Allen and others (1965) of the interval between magnitude 8 shocks on the San Andreas fault in southern California based on this approach is 18,300 years, which they concede seems "grossly misleading.

These statements of recurrence inter val (sometimes referred to as return period) do not imply that one magnitude 8 earthquake can be expected regularly every 700 years, but rather that over geologic time this would be the average A better way to state this relation is that there is a 1-in-700 chance (or .14 percent chance) of a great earthquake each year. Even this grossly oversimplifies the problem because it assum a statistical homogeneity and ignores the likelihood of clustering of events in time. Clustering of major events ma be more common than we can now tell fro the short recorded history of the fault so that several major earthquakes may occur within a century, separated by a thousand years or more of no large

Figure 5. Stream channel offset about 150 m. Temblor Range in background.

Figure 6. Pattern of channels appears to be controlled by en echelon fractures over the San Andreas fault zone. Note that these are right-stepping, comparable to thrust shears (see Wallace, 1973).

events. In the Caliente Range, Clifton (1968) found sedimentary cycles suggesting tectonic "events (or closely spaced flurries of events) with a periodicity of tens of thousands of years" which he relates to possible recurrent movement along the San Andreas fault.

WHERE TO SEE FAULT FEATURES

A field trip to see excellent features of the fault can be taken on secondary roads between State Highway 58 near Simmler and Highway 33 west of Maricopa. For a field guide map in this area, see the map by Vedder and Wallace (1970).

Starting at State Highway 58 (formerly 178) near Simmler (between Bakersfield and San Luis Obispo), one can take a dirt road in sec. 17, T. 31 S., R. 2 E., southeast from sec. 17, T. 31 S., R. 2 E. The road runs within a few metres of the fault marked by a northeast-facing scarp. In secs. 33 and 34 is one of the clearest examples of stream channel offset (see Fig. 5). Nearby in sec. 3, T. 31 S., R. 20 E., are excellent examples of sags and sag ponds. This is one of the longest (about 14 km) and straightest fault strands of the entire San Andreas fault system. Displacement, as indicated by offset streams, appears to die out to the southeast on this fault strand to be taken up on the next strand to the southeast.

In secs. 29 and 33, T. 31 S., R. 21 E., an elongate graben is well displayed. In its northwestern half, small fault-bounded blocks lie between the two bounding faults and appear in aerial photographs almost as "roller bearings" between the two blocks. In the NW¼ of sec. 11, T. 32 S., R. 21 E., is an excellent set of offset channels, one of which is shown in Figure 1 and may have been offset in 1857.

Along the Elkhorn scarp in secs. 29 and 33, T. 32 S., R. 22 E., an elongate ridge, essentially a shutter ridge, diverts the major drainage from the Temblor Range. Numerous narrow benches and fresh-appearing scarplets in this area may reflect 1857 movement. Sigmoi grabens are to be found in sec. 34, T. 32 S., R. 22 E., northeast of the Elkhorn scarp (see Fig. 4).

A complex zone of modified _en echelo_ fractures, rather than a continuous, linear fracture, marks the main trace o the fault in sec. 22, T. 11 N., R. 25 W (see Fig. 6). Strain may be distribute across the entire 1- to 2-km width of the Elkhorn Hills.

From State Highway 33, for a distanc of about 4 km northwest, is a series of well-developed sags and sag ponds. Fro Highway 33 southeast a good paved road follows the fault for about 5 km, cross ing the fault twice before winding and climbing to the southwest. Numerous linear ridges representing slivers of rocks between fault strands are visible here.

ACKNOWLEDGMENTS

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SECTION 5

Field Trip Guide

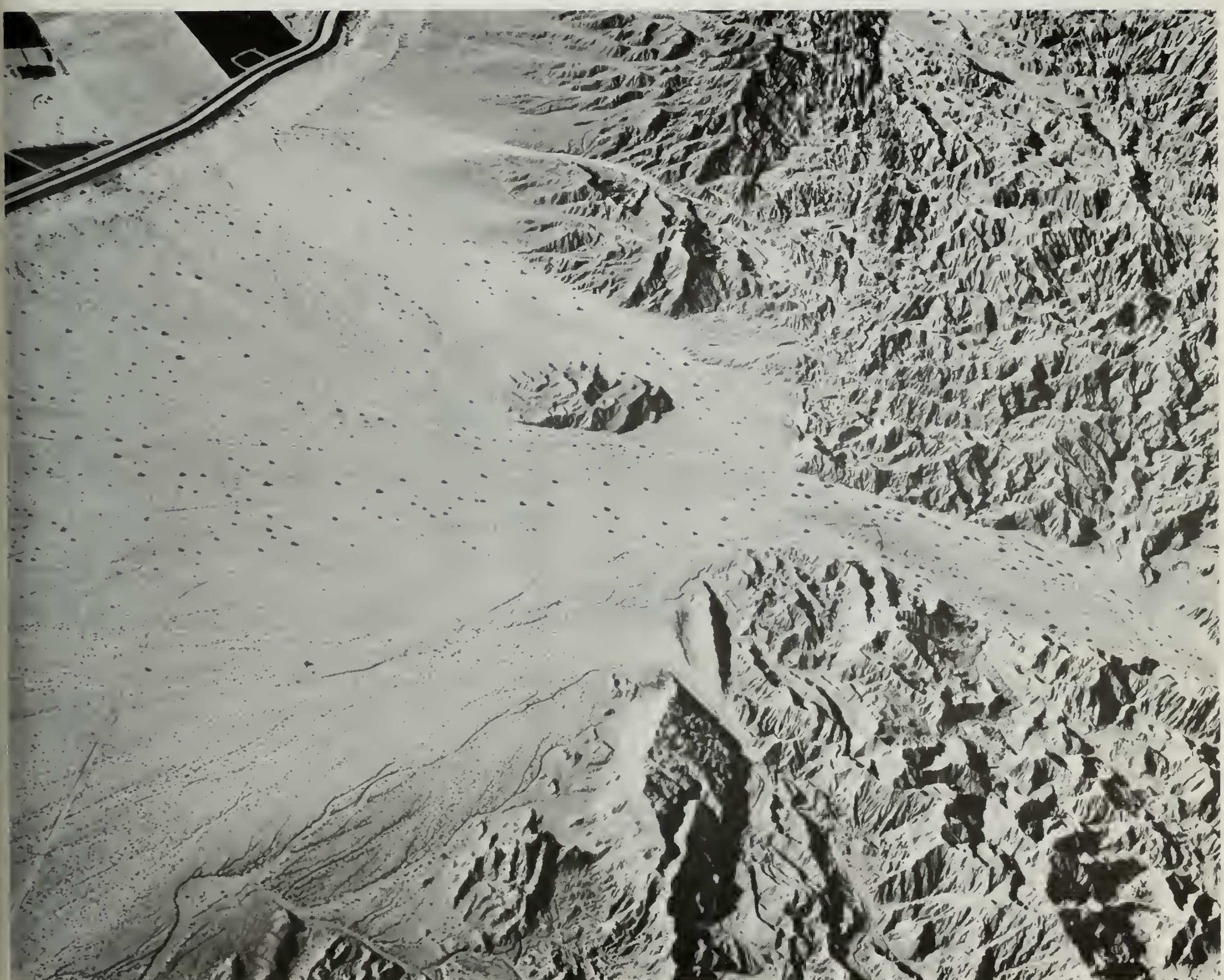

Photo 9. Mouth of Painted Canyon, Mecca Hills, looking northwest. Skeleton Canyon, in foreground immediately to right of the darkly shadowed hills, contains the trace of San Andreas fault.
J. S. Shelton Photograph No. 6818, 24 Nov. 1974, 6500 ft. elevation.

Photo 10. Looking northwest up Lone Pine Canyon which contains the San Andreas fault. This view is taken just southwest of Cajon Pass. Cajon Creek, with railways and freeway (Interstate 15), in foreground. Note Lost Lake, a sag pond in center foreground along the fault just across Cajon Creek, the railways, and the freeway.
J. S. Shelton Photograph No. 6849, 24 Nov. 1974, 8500 ft. elevation.

FIELD TRIP GUIDE TO THE SAN ANDREAS FAULT IN SOUTHERN CALIFORNIA

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RODUCTION

Although this guide was especially pared for a 3-day bus trip, it is in- eded for general use by individuals and ups who wish to become acquainted with features and problems of the San reas fault in southern California. The de starts near the Salton Sea and ends th of Bakersfield. More points of erest are included in the guide than be observed on a single three-day p. This has been done to permit rs of the guidebook to select among ps and to organize one- and two-day ps along segments of the route.

Instructions on how to reach points of erest are enclosed in [ ]. Mileage m reference points is underlined. rting points are marked by <u>0.0</u>. You l find it helpful to trace out the nerary on the southern half of the logic Map of California (1972 ed.; le 1:750,000) which accompanies this debook.

CA HILLS TO SAN BERNARDINO

[Starting on the east side of Indio the intersection of Dillon Road and te 86-111 proceed southeastward to ca on State 111, as shown in Fig. 1. dio is about 130 mi. from Los Angeles.) <u>10.8</u> turn left on State 195 into Mecca. road crosses the Southern Pacific lroad tracks, passes through the town Mecca and proceeds east toward the ca Hills.]

Indio (el. -14 ft.) and Mecca (el. 9 ft.) are within the Salton Trough. s region has periodically been flooded the Colorado River. As recently as) years ago all of the area below the vation of 45 ft. above sea level was inundated by Lake Coahuila whose shoreline features are well preserved. Shells of tiny gastropods which lived within it are ubiquitous within the lake bed sands.

<u>15.8</u> [Road crosses Coachella Canal; proceed 0.5 mi. to turn off to Painted Canyon. Highway 195 continues ahead into Box Canyon.]
<u>16.3/0.0</u> [Turn left (west) onto graded gravel road leading to Painted Canyon.)

To the north lie the Mecca Hills with deeply incised badlands topography. The modern San Andreas fault trends northwest across the southern margin of the hills. Streaks of red clay gouge mark its location. Dark gravel-strewn slopes in the foreground are underlain by Pleistocene Ocotillo Conglomerate which contains abundant schist debris derived from the Orocopia Mountains to the east and subsequently offset by several miles of right slip along the San Andreas fault. The ruggedly sculptured part of the Mecca Hills is underlain by the Pliocene-Pleistocene Palm Spring Formation. It consists mainly of sandstone and conglomerate deposited as alluvial fans descending southward from the Little San Bernardino and Cottonwood Mountains to the north. Greenish lacustrine beds of micaceous sandstone, siltstone and claystone interfinger with fluvial beds in the southern part of the hills. The Palm Spring Formation unconformably overlies a faulted mosaic of heterogeneous basement rocks within the pre-Pleistocene San Andreas fault zone. The hills have formed since mid-Pleistocene time by a combination of broad arching and smaller-scale folding and faulting. As uplift proceeded drainage from the Little San Bernardino and Cottonwood Mountains continued to flow southward through incised canyons, including Box Canyon and Painted

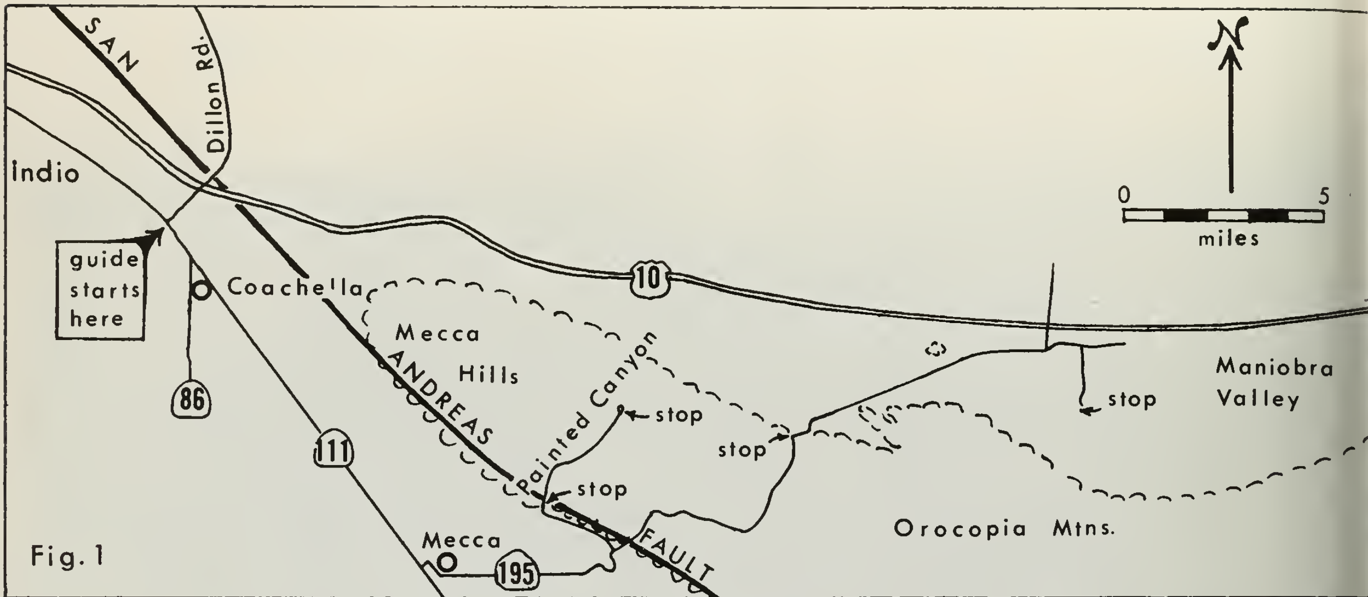


Fig. 1

Canyon. The geology of Painted Canyon is described by Sylvester and Smith (this vol.).

2.6 [As you enter Painted Canyon turn right on dirt road; proceed 0.2 mi. and park near clay pit.]

2.8 Skeleton Canyon Stop

The San Andreas fault trends N45°W across the mouth of Painted Canyon and into Skeleton Canyon. The red material on the ridges and in the clay pit is gouge. Examine exposures in bulldozer cuts directly east on the south side of Skeleton Canyon. Slickensides occur here with many orientations indicating a complex pattern of movement within the gouge zone. Excellent exposures are also present 0.5 mi. up Skeleton Canyon displaying a drag fold and large phacoids of sandstone encased in clay gouge.

From the mouth of Skeleton Canyon walk southward around the ridge spur and southeastward along the base of the main ridge for nearly 1500 feet. Take the trail over the low ridge and descend into Aiken's Corner (locality H is in Fig. 1, Sylvester and Smith, this vol.). Observe the tight, steeply plunging drag folds in the Palm Spring Formation. (The formation is soft so avoid stepping on embossed parts of the folds.) Continue down the wash to where steeply dipping beds of Ocotillo Conglomerate contain abundant clasts of gray Orocopia Schist. Clast imbrication indicates derivation from the northeast, and from a schist source area now displaced by right slip on the San Andreas fault.

[Return to vehicles and proceed up Painted Canyon.]

3.5 Note anticline and syncline on west side of canyon and great thickness of the Palm Spring Formation between here and the next stop.

3.7 Green siltstone bed east of road contains abundant tiny shells of fresh-water gastropods indicating deposition in a fresh water lake.

4.2 Drag folds along minor fault on west side of canyon separate light colored beds of Palm Spring Formation on south from red, locally derived sandstone, conglomerate and breccia of the Mecca Formation on north.

4.5 Sheared and altered gneissic basement, squeezed upward within the core of a major anticline.

4.7 On west side of canyon vertical beds terminate downward along buttress unconformity. Beds were originally deposited against a southwest-facing fault-line scarp in the basement rock and later tilted 90 degrees (see Sylvester and Smith, this vol.).

.9 Painted Canyon Anticline Stop

[Graded road ends here but cars can usual-
y proceed to next stop up north branch of
ainted Canyon without difficulty. Buses
ıust turn around here.]

Tight, faulted folds are exposed on the idge east and a chevron anticline is exosed at the mouth of Anticline Canyon to he west. This zone of strong deformaion trends northwestward through the enire length of the Mecca Hills. It overies the Painted Canyon fault, an inactive ranch of the San Andreas, which formed a outhward-facing scarp during deposition f the Mecca and Palm Spring Formation. hese formations are several thousand eet thick and strongly deformed to the outhwest of the Painted Canyon fault but nly a few hundred feet thick and gently eformed to the northeast.

Anticline Canyon, well worth exploring, rovides a path to the top of the ridge ith spectacular views of the Painted anyon fault zone and the Mecca Anticline ith a core of deformed basement. When ou reach an apparent impass at a dry aterfall with a bedding plane thrust xposed in the west wall, climb through he collapsed blocks partially concealing he canyon to the north and proceed hrough a narrow passage.

After completing this stop, walk or drive p the north branch of Painted Canyon.]
.4 Entrance to Ladder Canyon on north-
est; an excellent place to observe a
arrow, vertically-incised canyon.
.5 Gneiss exposed unconformably beneath
alm Springs Formation. Locally derived
ed breccia of the Mecca Formation fills
ow spots in the unconformity.

.8 Anorthosite Stop

A low dry waterfall prevents vehicles
rom going further up canyon.]

Complexly folded migmatitic gneiss is xposed in the canyon wall. It is probbly Precambrian in age but has not been ated. Proceed up canyon. Volcanic dikes intrude the gneiss in several places. About 500 feet up canyon, white, highly altered anorthosite is faulted over gneiss. The fault is truncated by the unconformity at the base of the Palm Spring Formation. Continue up canyon through the second main bend to the left. Here the anorthosite and related dioritic rocks are cut by a dike of porphyritic, rapakivi-textured quartz latite porphyry similar to dikes in the northern Chocolate Mountains (see Ehlig, Ehlert and Crowe, this vol.). Clasts of this rock type occur in the Mint Canyon Formation in Soledad Basin to the west of the San Andreas fault and in the Caliente Formation near Frazier Park to the west of the San Gabriel fault.

A few small exposures of fairly fresh anorthosite and related rocks occur up canyon. Orocopia schist is also exposed but can be seen more easily at Shaver's Well.

0.0 [Painted Canyon turnoff and State 195; turn left and take State 195 into Box Canyon.]
0.5 San Andreas fault crosses highway.
1.0 Skeleton Canyon fault marked by change in dips west of road.
1.5-1.6 After rounding turn, a local angular unconformity is visible in Palm Spring Formation to left (south); slow down or stop as road curves to north to observe unconformity ahead to left (north). It indicates tectonic activity during deposition.
3.0-3.7 Road obliquely crosses same zone of deformation as seen at Painted Canyon Anticline. Note folds.
3.5 Tight syncline on ridge spur ahead to right (south) of road.
6.9 Buttress unconformity of Palm Spring Formation against Mesozoic(?) Orocopia Schist. Alluvial terrace gravels are also present.

7.1 Shaver's Well Stop

[Park near trees on left side of road.]

Orocopia schist exposed here consists mainly of green actinolite-chlorite-epidote-albite schist derived from basic volcanics; the more common gray muscovite-albite-quartz schist, derived from graywacke, siltstone and shale, is exposed a short distance up canyon. Banded quartzite layers are metamorphosed chert. Milk quartz is of vein origin. The Orocopia Schist is identical to Pelona Schist seen later.

7.3 Fanglomerates dip north as road exits from Mecca Hills.
8.8 View east along Orocopia thrust with Orocopia Schist to south and Precambrian syenite to north.
10.2 Dirt road turnoff for those wishing to see syenite in outcrop. The Syenite is considered the same as that south of the San Andreas fault near Palmdale.
11.5 Conglomerate and sandstone of the Eocene marine Maniobra Formation unconformably overlies granitic rocks on the hill to west.
14.2 [Intersection with Pinto Rd; Interstate 10 to north. To see Eocene Maniobra Formation take Pinto Rd. east 0.6 mi. then turn south on dirt road; proceed 1.3 mi. then park next to ridge on right.]

16.1 Maniobra Formation

Coarse conglomerate and breccia are the dominant lithology in this area, but with some calcareous sandstone. Fossil fragments occur in yellow silty layers and in clasts of silty sandstone. The main fossil localities are five miles east in Maniobra Valley (see Crowell and Susuki, 1959, for details). This isolated occurrence of Marine Eocene presents difficulties for reconstruction of Eocene paleogeography (see Howell, this vol.).

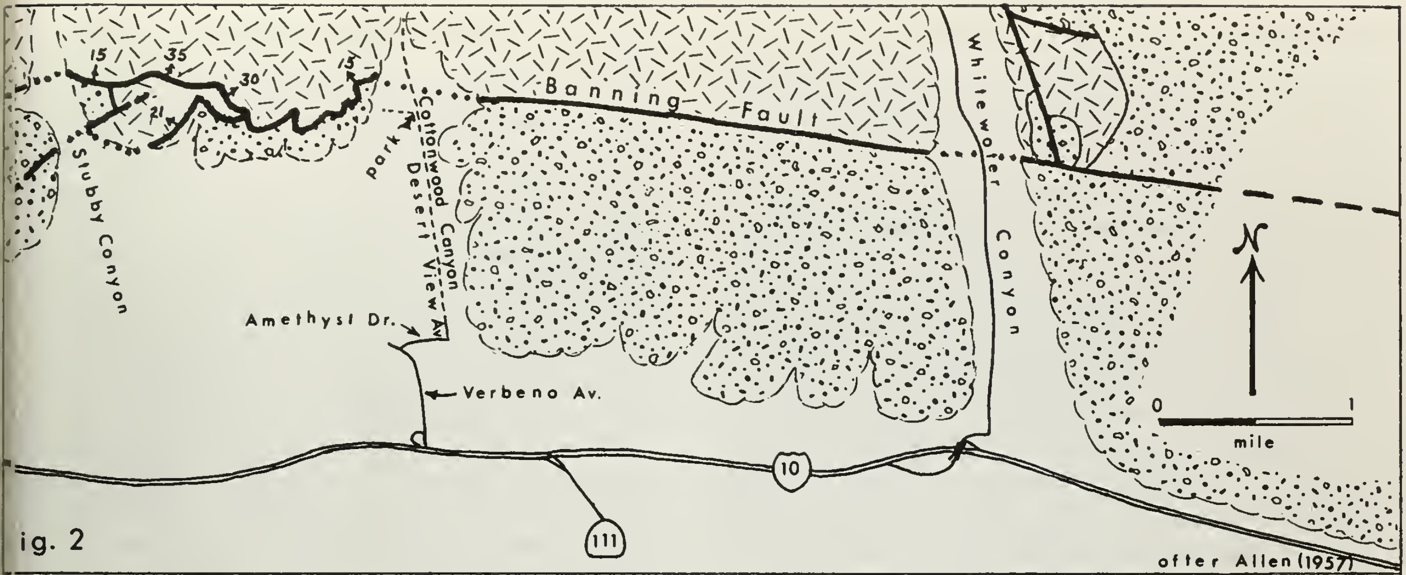
Clasts of syenite and anorthosite (rare), eroded from the hills to the south, can be collected from the alluvium in this area for comparison with similar rocks south of the San Andreas near Palmdale. The syenite is a dark rock composed mainly of feldspar (mesoperthite).

[Return to westbound Interstate 10.]
0.0 [Entering Interstate 10 westbound.]
18.1 Ahead to right Ocotillo Conglomerate is steeply tilted and unconformably over lain by old alluvium. Fault scarp on northeast side is clearly visible on aerial photos.
22.1 [Take Dillon Road north for scenic drive along north side of Indio Hills; then take Thousand Palms Canyon Road south through the hills and rejoin Interstate 10 at Kubic Road in Thousand Palms

The San Andreas fault crosses Dillon Road 0.6 mi. north of Interstate 10. Prominant vegetation occurs on the north side due to impounding of southward-flowing ground water. Several groves of native Washingtonia palms mark springs along the San Andreas fault in the Indio Hills. The fault splits into a north branch (Mission Creek fault) and a south branch (Banning fault) which bound the main body of the Indio Hills west of Thousand Palms Canyon. Most of the pre-Pleistocene offset was probably along the north branch as shown by the apparent offset of formations exposed in the San Bernardino Mountains (see Dibblee, this vol.).

The Indio Hills are similar to the Mecca Hills. Pleistocene fanglomerate (Ocotillo Formation) is the most widely exposed formation. The Palm Spring Formation is extensively exposed in the eastern part of the hills and locally elsewhere. The Miocene-Pliocene marine Imperial Formation, consisting of fine-grained sandstone and claystone, forms conspicuous yellow-brown outcrops along the southern base of the hills a mile west of Thousand Palms Canyon at Willis Palms. These exposures are accessible by car. Exposures also occur in the northwestern part of the Indio Hills. The formation is not known to occur east of the Mission Creek branch of the San Andreas fault.

0.0 [Interstate 10 west bound at Kubic Road in Thousand Palms (25 mi. by way of Dillon Road and Thousand Palms Road but 15 mi. by freeway from Dillon Road and Interstate 10).]
9-10 Garnet Hill on left (south) is domed up along the north side of the



ig. 2

arnet Hill fault. A cap of coarse fan-
lomerate, including breccia, derived
rom the San Jacinto Mountains to the
outh overlies the Imperial Formation.
) A line of vegetation marks the Banning
ranch of the San Andreas fault to the
orth. San Gorgonio Pass is straight
head to the west with the San Bernardino
ountains on the right (north) and the
an Jacinto Mountains on the left (south).
4 An anticline in Pleistocene Cabazon
anglomerate forms the hill on the right
north).
5.3/0.0 [Take Whitewater turnoff; go
ight (north) up Whitewater Canyon (see
ig. 2).]
efer to Petersen (this vol.) and Allen
1957) for the geology of this area.
.5 Banning fault trends N85°W across
anyon placing Cabazon Fanglomerate on
outh against granitic and gneissic rocks
n north. Note vegetation line where
ctive fault crosses alluvium in the can-
on bottom.
.1 On east side of canyon, Whitewater
ault (trending N30W) places old alluvium
gainst upper Miocene Coachella Fanglomer-
te.
.9 Road ends at Trout Farm. Coachella
anglomerate forms east wall of canyon.
ission Creek fault 3 mi. north; juncture
f Mission Creek and Pinto Mountain faults
mi. northwest (see Dibblee, this vol.).
Return to Interstate 10 and proceed 2.6
i. west to Verbena turnoff.]

From Cottonwood Canyon, 2 mi. west of Whitewater, to Millard Canyon, 6 mi. further west, the basement rocks north of Banning fault are thrust over sedimentary rocks to the south (Allen, 1957). As seen from Interstate 10, the thrust separates brown hills in the foreground from the steep greenish gray and white banded slopes to the north. The thrust is accessible on the east side of Cottonwood Canyon (next stop). The thrust occurs where the San Andreas fault bends abruptly, perhaps due to left slip along the Pinto Mountain fault (Allen, 1957, and Dibblee, this vol.).

26.1 Cottonwood Canyon Stop

[Refer to Fig. 2. The roads are unsuited for buses. Take Verbena Av. turn off from Interstate 10; follow Verbena Av. 0.4 mi. north; turn right (east) on Amethyst Dr.; continue 0.3 mi. then turn left (north) on Desert View Av. (gravel road rises onto flood control berm), continue north 1.2 mi. and park in broad area or take jeep road 0.1 mi. to west side of canyon.]

Pleistocene Cabazon Fanglomerate forms the lower gravelly slopes at west entrance of Cottonwood Canyon. Sheared granitic and gneissic rocks overlie it along a fault dipping gently northward. The fault is easily traced around a low ridge spur and adjacent canyon.

[Return to Interstate 10 at Verbena Av. and proceed 16.7 mi. west to Beaumont.]
0.0 [Take Beaumont Av. north from Interstate 10 to view the San Andreas fault at Oak Glen. Beaumont Av. changes to Oak Glen Rd.]
The road follows the west side of Little San Gorgonio Canyon. The dissected terrace surface along the canyon is a continuation of the surface that forms Banning Bench to the north of Banning.
8.8 Road swings west; the active south branch of the San Andreas fault is 0.4 mi. north. Old alluvium on south is faulted against gneissic basement on north. Young rift topography characteristic of the fault zone to the west ends 2 mi. to the southeast and is absent from there to the vicinity of Whitewater Canyon.

10.8 Oak Glen Stop

[Park just before hairpin turn, 1 mi. west of Oak Glen Village.]

This stop is on a shutter ridge within the San Andreas fault zone. Basement rocks form steep terrain across the fault zone to the north. There is a prominent scarp along the south side of this ridge. Seeps occur along the base of the scarp beyond which is a steep westward descending alluvial fan. Looking northwest on a clear day, the San Andreas zone is a clearly etched groove in the topography. The fault bends conspicuously to the right toward Cajon Pass; the eastern San Gabriel Mountains rise behind and left (west) of Cajon Pass.

Note houses in the Oak Glen area; if an earthquake occurs here, many are likely to experience severe damage due to construction on steep slopes and soft ground within the fault zone.

15.7 [Intersection of Oak Glen Rd. and Bryant St.; turn north on Bryant St. and continue to Mill Creek Rd.]
18.0 [Turn right (north) on Mill Creek Rd. (State 38).]

19.1 Potato Sandstone Stop

[Park in turnout on west side of road opposite historical mounument.]

The active south branch of the San Andreas fault is concealed by alluvium 0.3 mi. to the south; the inactive north branch is 2 mi. to the north. Sheared basement rocks are exposed in road cuts the south of the parking area and Pliocene Potato Sandstone is exposed to the north. Examine the Potato Sandstone in exposures below the road and in the vicinity of the south abutment of Mill Creek Bridge. Here the formation consists of conglomerate and sedimentary breccia wit abundant clasts of Pelona Schist or Orocopia Schist along with granitic and gneissic clasts. Suggestions of imbrica tion imply transport from the southwest the northeast. Beds of sandstone and siltstone with ripple marks and bottom lineations are locally present. Bluffs north of the bridge expose well bedded sandstone and shale with tongues of schist breccia. The Potato Sandstone is believed to have been deposited in a trough along the south side of the north branch of the San Andreas fault. Data acquired by Gibson (1971) indicates that the sediments were derived primarily fro the north, probably from the Orocopia Mountains. The beds are therefore offse about 60 mi. laterally from their probable source.
0.0 [West bound on Mill Creek Rd. (Stat 38) at Bryant St.]
The Crafton Hills are to the southwest. South-dipping Pelona Schist crops out in the northern part of the hills. The schist is overlain, to the south, by cat clastic rocks of the Vincent thrust, above which are granitic and gneissic rocks (see Ehlig, this vol.).
1.1 Light rocks in the hillside and roa cut are dikes and sills of Miocene quart latite porphyry which intrudes Pelona Schist.
3.1 [Turn right (north) on Garnet St.
4.1 the road turns left (west) and becom Forida St.; 0.8 mi. farther the road tur north and becomes Greenspot Rd. Continu across wash and park north of bridge.]

.0 Santa Ana Wash Stop

The San Andreas fault is exposed in the luff on the east side of the wash. rushed granitic rocks occur to the north f the fault and old alluvium occurs to ne south. Note the huge boulders in the ash. The Santa Ana River drains a large rea within the San Bernardino Mountains nd occasionally experiences high runoff.

Follow Greenspot Rd. 5 mi. to State High-ay 30; turn right and proceed 1.7 mi. to ntersection of Highland Av. and State ighway 330.]

AN BERNARDINO AREA

There has been extensive construction long the San Andreas and San Jacinto ault zones within this area making it deal for the study of potential risks and azards attendant upon such construction. hat types of structures should be per-itted along the faults and within the ault zones, what special engineering recautions are needed and how great is he resulting risk to life and property? pinions vary, only hindsight can afford n absolute answer.

Refer to Morton (this vol.) and Morton nd Miller (this vol.) for a discussion of aults in the San Bernardino area.

an Andreas Fault Zone Stops

The San Andreas fault zone is exten-ively developed along the foot of the San ernardino Mountains from State 330 (the ighway to Running Springs and Big Bear ake) westward to San Bernardino State ollege. Expensive homes are built within he fault zone and there is an apparent ropensity to place water tanks immediate-y uphill from scarps. The following are ut a few of the points worth seeing.

[Start at the intersection of State 330 nd Highland Av. (see fig. 3). Go west on ighland Av. for 0.7 mi. then turn right north) on Palm Av. Continue to the end nd then go right (east) on Citrus St. to he end.] Here, a new tract has been developed across the fault zone. A large water tank is on the hill above the scarp and an elementary school is on the valley side of the scarp.

[Proceed 1.0 mi. west on Highland from Palm Av. and turn right (north) on Victoria Av.; continue 0.8 mi. north then turn right (east) on Lynwood Dr. to Serrano Junior High School.]
The two water tanks to the northeast are along the fault zone. The junior high school appears to be just south of the fault.

Drive north on Victoria Av. from Lynwood Dr. 0.2 mi. and then turn left (west) on Marshall Blvd.; continue 0.5 mi. then right (north) on Arden for 0.2 mi. to Foothill Dr., turn left and continue 0.2 mi. west to Manzanita Dr.; turn right (north) and drive uphill across the fault scarp. Road curves east and becomes Willow; take Willow to end.]
Note the fault trench to the east, the water tank to the north and the fault scarp to the south.

San Bernardino State College is a mile east of Interstate Highway 15 directly southwest of the San Andreas fault. Good scarps occur along the foot of the mountains to the northeast. The campus is on alluvium which conceals faults which may be present beneath the site.

Those wishing to observe the Cucamonga fault zone along the foot of the San Gabriel Mountains to the west should refer to Morton (this vol.).

Interchange of Interstate 10 and 15 (San Bernardino and Barstow Freeways)

This artistic interchange with high overpasses straddles the San Jacinto fault (Fig. 4).

San Bernardino Valley College Stop

[The campus can be reached by going north on Mt. Vernon Av. from Interstate Highway 10 or west on Mill St. from Interstate Highway 15 as shown in Fig. 4.]

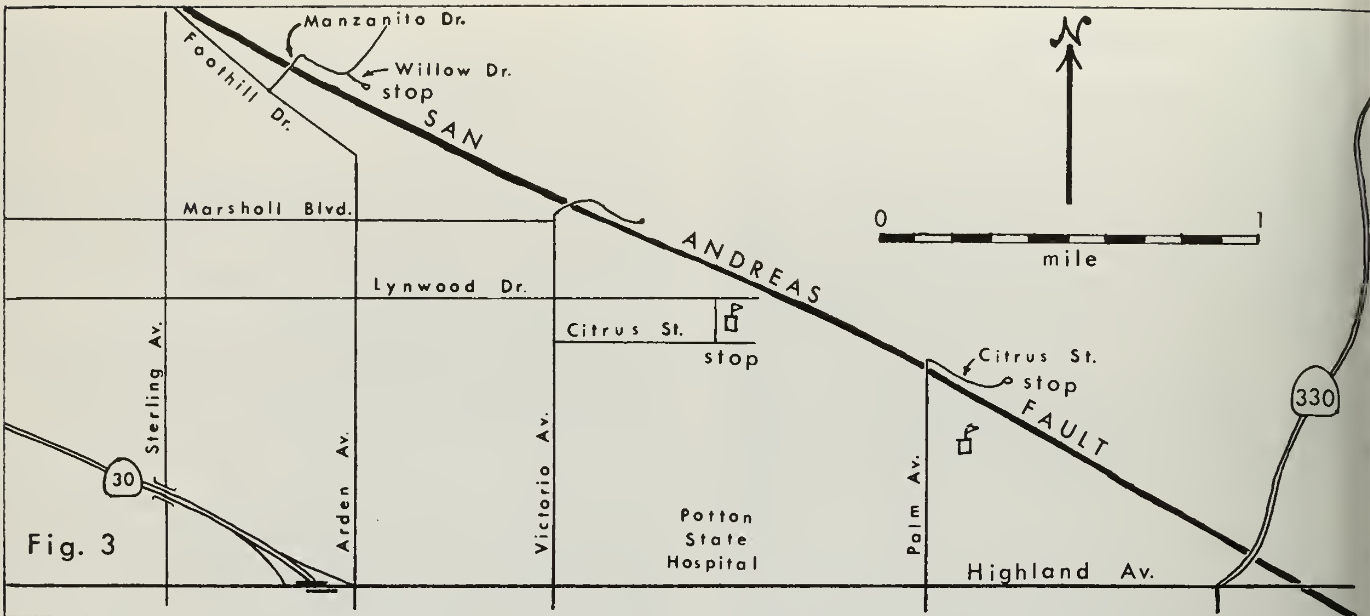


Fig. 3

The campus is constructed on Bunker Hill which is a pressure ridge along the San Jacinto fault. When construction began in 1926, the hill was believed to be an anticline in tertiary sediments. In 1935, when its true nature was learned, John P. Buwalda of the California Institute of Technology was engaged to make a study. Buwalda recommended strengthening of existing buildings and recommended against placing future buildings across fault scarps, but he did not consider it necessary to move the campus. Additional detailed studies have been undertaken in recent years. Refer to Allen (1971) for further information.

CAJON PASS TO PALMDALE

[Take Interstate 15 (Barstow Freeway) north from San Bernardino. Turn off at Devore Rd. on south side of Cajon Pass (Fig. 5).]

0.0 [Devore Road turnoff from Interstate 15. Go north on Devore Rd. 1.0 mi., turn left (northwest) on Kenwood Rd. and continue 0.4 mi. to Kimbark Elementary School.] Note the north facing scarp in the alluvial terrace south of Kenwood Rd.

1.4 Kimbark School Stop

Kimbark Elementary School, completed in 1969, is within a prominant trough to

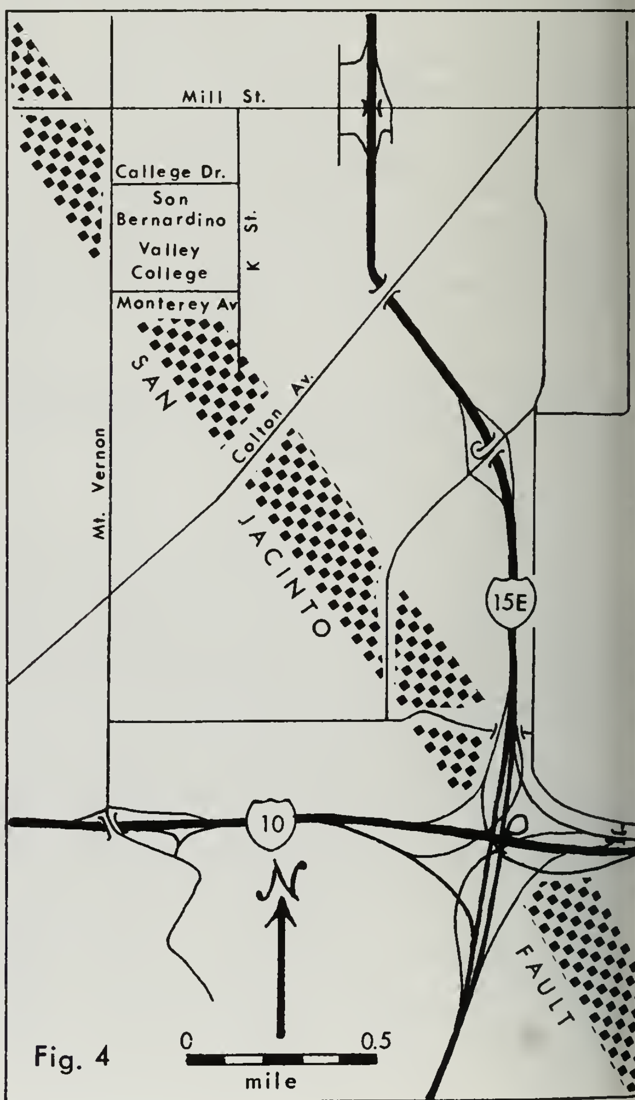


Fig. 4

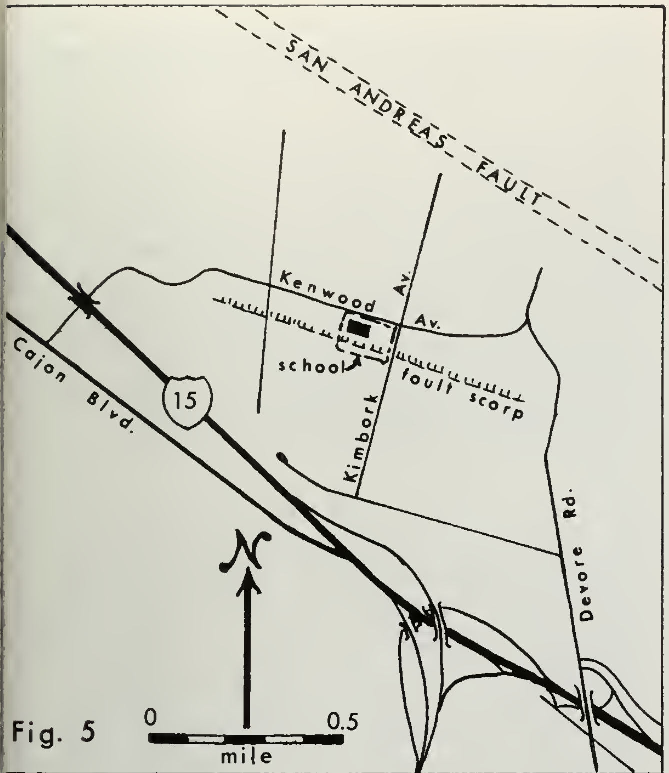


Fig. 5

outh of road. A backfacing scarp of an ctive fault trends northwest across the layground at rear of school. The scarp s well exposed on the east side of Kimark Av. The main San Andreas fault is o north at base of slope.

Continue northwest on Kenwood, pass under nterstate 15.]
.5 [Cajon Boulevard; turn right and go orth into Cajon Pass.]

Road cuts are in Mesozoic(?) Pelona chist. This schist forms exposed baseent along the south side of the San ndreas fault for nearly 50 miles in this rea but does not occur north of the ault. The well bedded, gray-colored chists are muscovite-albite quartz chists derived from interbedded grayacke, siltstone and shale.

.4-6.7 Blue Cut Stop

After rounding the turn note the heavy ence constructed along part of Blue Cut o prevent fractured quartz diorite from alling on road. The quartz diorite is n a fault slice with Pelona Schist on either side. Note the unfaulted, nearly horizontal unconformity at base of alluvial terrace above railroad tracks. Although this terrace may be only a few thousand years old, it indicates the underlying bedrock is quite rigid. Much of the Pelona Schist exposed along Cajon Creek below the terrace is in a coherent condition.

The San Andreas fault crossed Cajon Creek at the northern edge of the gray-green outcrops in the canyon bottom (at 6.7 mi.). Cajon Canyon is offset obliquely about 1.5 mi. right laterally. A small ravine in old alluvium between Cajon Creek and Lost Lake (to west) is offset 0.2 mi. to the right.

7.3 North dipping Paleocene marine sandstone, siltstone and conglomerate rest unconformably on gneissic basement. Lower Miocene marine rocks also occur north of the San Andreas in Cajon Valley.
7.4 [Turn left and follow road past Cajon Campground and southward across railroad track.]
8.0 San Andreas fault crosses south of house with red tile roof.
8.4 [Pavement ends; take gravel road to right along power line; go 0.1 mi. then take left branch 0.2 mi. to Lost Lake.]

8.7 Lost Lake Stop

Lost Lake is a spring-fed sag pond along the San Andreas fault. The lake retains water throughout the year despite high evaporation rates during summer and its elevation of about 150 feet above nearby Cajon Creek.

The trace of the San Andreas trends N55°W up Lone Pine Canyon and forms the notch in the hill beyond Interstate 15 to the southeast.

10.0 [Return to Cajon Blvd. and continue north 2.2 mi. to freeway entrance.] The Miocene Punchbowl Formation forms colorful ridges to the northwest.
12.2 [Enter northbound Interstate 15; continue 0.8 mi. and take the Wrightwood turnoff (State 138). Go right (east)

0.2 mi. on State Highway 138 and park in broad area on south.]

13.2 Crowder Stop

The Pliocene to lower Pleistocene (?) Crowder Formation, consisting of fluvial sandstone and conglomerate, is exposed in the cut to the north. Clasts include common granitic rocks, a distinctive dark fine-grained spotted phyllite and some volcanic rocks. Clast imbrication indicates derivation from east or northeast (eastern part of cut). The bulk of hill to the north of the cut consists of granodiorite with the Crowder Formation deposited against it along a buttress unconformity.

0.0 [Head west on State Highway 138; start mileage at Interstate 15.]

2.0 Mormon Rocks Stop

[Park well off of the road to the west of the low saddle beyond Mormon Rock Ranger Station. Watch out for fast moving vehicles.]

The hogbacks are formed from northeastward tilted sandstone and conglomerate of the Miocene Punchbowl Formation which is of fluvial origin. Clasts include volcanic and granitic rocks and spotted phyllite. Clast imbrication indicates derivation from the northeast. The detailed stratigraphy is described by Woodburne and Golz (1972) and by Woodburne (this vol.).

The type Punchbowl Formation is exposed 20 mi. west in Devil's Punchbowl to the south of the San Andreas fault. Noble (1954) considered the type section to have originated opposite the Cajon Valley beds and to have been subsequently offset by right slop along the San Andreas fault. Such an explanation, however, poses difficulties because evidence elsewhere suggests that this branch of the San Andreas should have about 125 mi. of post Miocene right slip, not just 20 mi. Studies by Woodburne and Golz (1972) show that the Cajon beds are middle to upper Miocene in age whereas the Punchbowl Formation of the type area is early Pliocene in age. The type area was also deposited by streams flowing from the east and northeast (Pelka, 1971) and contains granitic and volcanic clasts; however phyllite clasts found in the Cajon Valley beds ar not present in the type area whereas the type area contains distinctive clasts o "polka-dot granite". This distinctive rock is a quartz monzonite containing large cordierite crystals partially weathered to iron oxide. It is absent from beds in Cajon Valley.

The bluffs along the skyline to the northeast consist of Pleistocene alluvi gravels derived from the San Gabriel Mountains to the south. The upper gravels at Cajon Summit consist almost entirely of Pelona Schist clasts. The lowest part of the section contains clasts of Lowe Granodiorite and other rock types found in place within the central and western San Gabriel Mountai as well as clasts of Paleocene sandston and rare "Polka-dot granite", probably derived from the Punchbowl Formation in Devil's Punchbowl. This suggests that 20 to 25 mi. of right slip has occurred along this strand of the San Andreas fault since deposition of the lower bed These gravels provide the first indication of the rising of the San Gabriel Mountains to the south of this area.

[Continue west on State Highway 138 for 6.6 mi.]

8.6/0.0 [Turn left onto State Highway and proceed toward Wrightwood.]

1.5 Cajon Valley fault crosses the rid to the east. Steeply inclined beds of Punchbowl Formation crop out northeast the fault and basement rocks crop out t the southwest. Basement rocks to the north of the San Andreas fault in this area consist of granitic rocks (quartz monzonite to quartz diorite) and migmatitic gneiss containing pods and layers o marble. These rocks have not been date but the marble and gneiss are probably derived from Paleozoic strata and the granitic rocks and metamorphism are robably Cretaceous. Similar rocks crop ut at the west end of the San Bernardino ountains.

.6 The large white area on the mountain head is a marble quarry.
.2 Sheep Creek, to west of the road, is oted for mudflows of Pelona Schist debris. he flows originate in a landslide area n the north side of Wright Mountain 8505 ft.) at the head of Heath Canyon, irectly south of Wrightwood. The dark chist fragments makes Sheep Creek's aluvial fan stand out on the ERTS photo of his area.

The town of Wrightwood is spread across warthout Valley, eroded along the San ndreas fault zone to the west of Lone ine Canyon. The 1857 fault break (idenified by trenching) is along the downill side of Wright lake and Twin Lakes, pslope from the main part of town. Aluvium covers most of the valley floor so here is uncertainty regarding the conition of the underlying bedrock.

To the west of Wrightwood, a half mile eyond the Los Angeles-San Bernardino ounty line, the highway skirts the top f the 1857 scarp. A highway maintenance tation rests on alluvium on the uphill ide to the north; a marshy area lies to he south.

.7/0.0 Big Pine Junction Pause Stop

The 1857 scarp is on the north side of he intersection and extends behind the anger station to the east. The fire tation to the west is on saturated ground ithin the fault zone but is south of the 857 break.

The road goes 1.1 mi. to Table Mountain 7516 ft.) which affords an excellent view f the Mojave Desert. Note that the San ndreas fault slices across the San abriel Mountains at this location without any apparent vertical uplift along it. he mountains have been uplifted by arching as shown by northward dips of 20° to 0° in the oldest Pleistocene gravels long the foot of the range to the north.

At 0.2 mi. up Table Mountain Rd., folded beds of clay, silt and pebbly sand and gravel are exposed in the road cut downhill from marble outcrops. Shells of tiny gastropods and ostracods occur in some yellowish silty beds. These and similar beds, which occur sporadically along the fault zone to the west, were apparently deposited in sag ponds along the fault.

0.0 [From Big Pine Junction go left (southwest) on Angeles Crest Highway (State 2) to the top of Blue Ridge then park in the overview.] Blue Ridge is composed exclusively of Pelona Schist.

1.9 Blue Ridge Overview Stop

The Punchbowl fault, trending along the southern edge of Blue Ridge, is an old inactive strand of the San Andreas fault system with about 25 mi. of right slip along it (Dibblee, this vol.). It is not a continuation of the young, highly active San Jacinto fault.

Pelona Schist is exposed immediately south of the Punchbowl fault. Farther south the Vincent thrust places gneissic and plutonic rocks of the San Gabriel Mountains over the schist. The thrust crops out on Mt. Baden-Powell (9399 ft.) to the southwest at about eye level, a few hundred feet above a light colored swarm of Miocene dacite and quartz latite sills. A thick zone of mylonitic and retrograde metamorphic rocks forms the base of the upper plate. Thrusting occurred synchronously with prograde metamorphism of Pelona Schist during late Cretaceous or early Cenozoic (Ehlig, this vol.). The thrust crosses the north flanks of Iron Mtn. (8007 ft.) to the south and Mt. San Antonio (Mt. Baldy, 10064 ft.) to the southeast.

The eastern San Gabriel Valley and points beyond are visible to the south on a clear day.

[Continue west on Angeles Crest Highway to Vincent Gap.]

5.0 Vincent Gap Stop

The Punchbowl fault trends about N65°W through this gap. Red sandstone and conglomerate, Punchbowl Formation (?), exposed south of the parking area are in fault contact with basement rocks upslope to the south. A fault slice of granitic rocks intervenes between sandstone and Pelona Schist on the north side of the gap. A fault slice of sedimentary breccia, exposed on the ridge spur between Vincent Gulch and Prairie Fork to the southeast, contains blocks of syenite probably derived from outcrops west of Soledad Pass and offset by right slip.

[Return to Big Pine Junction]
0.0 [Big Pine Junction, take L.A. Co. Rd. 4N08 west along San Andreas toward Valyermo.]
2.8 Jackson Lake is a sag pond formed in part by a shutter ridge on north blocking canyon to south. A sliver of steeply dipping Pleistocene(?) sandstone and conglomerate crops out north of the road.
3.0 [Entrance to Jackson Lake.]
The Fenner fault is truncated by the San Andreas fault beneath the hill to the southwest. The Pelona Schist of Blue Ridge lies south of the Fenner fault and granitic and gneissic rocks capped by Paleocene marine sandstone lie to the north. The Fenner fault is considered to be an eastward continuation of the Francisquito-Clearwater fault which has been offset 25 mi. to the right along Nadeau-Punchbowl fault (Dibblee, this vol.).
4.0 Excellent view looking west along trace of San Andreas to Tehachapi Mtns. From here to Coldwell Lake fault rift topography, including prominent trenches and shutter ridges, occurs along the north side of the road.
7.3 Coldwell Lake, the small sag pond in the half-mile long depression to the south is probably the offset head of Grandview Canyon to the east.
From here to Big Rock Creek, Pleistocene gravels occur along and to the north of the fault.
11.6 [Turn left (south) onto Big Rock Creek Road.]

Gneissic and granitic rocks of Pinyon Ridge to the east are unconformably overlain by the Paleocene marine Francisquito Formation (Sage, this vol.). To the southwest, the Pliocene Punchbowl Formation unconformably overlies Paleocene strata in the Devil's Punchbowl, an area of spectacular exposures formed by differential erosion of strata within a westward plunging syncline.

12.7 Big Rock Creek Stop

Sandstone and conglomerate of the Francisquito Formation are well exposed on both sides of the canyon.

[Continue up canyon past upper Big Rock Creek turnoff.]
Thinly interbedded siltstone and sandstone of the Francisquito Formation are exposed on the slope west of Big Rock Creek. Across the valley to the southeast, the Punchbowl fault separates red sandstone of the Punchbowl Formation from gray basement rocks.

15.2 Paradise Springs Stop

[Park off road 0.2 mi. east of Paradise Springs turnoff.]

Siltstone and sedimentary breccia of the Francisquito Formation rest unconformably on granitic and gneissic basement upslope to the north. The breccia beds are easily mistaken for basement in place but can be distinguished by rounded pebbles and cobbles scattered through the matrix. The unconformity is an uneven surface which has been tilted southward. Good boots and a vigorous hike are required to visit the outcrops.

[Return to entrance to Big Rock Creek.]
0.0 [Turn left and go west on Valyermo Rd.]
0.3 From Bob's Gap Rd. to Pallett Creek the main San Andreas fault is south of the road but the zone of disturbed rock nearly a mile wide. Holcomb Ridge to the north consists of relatively unfaulted granitic rocks with a marble pendant trending N70°W along the crest.

2.8 [Turn left (southwest) on Pallett Creek Rd.]

2.9 A veneer of alluvium is down-faulted against bedrock in the cut beneath the stone house on the right. In the cuts ahead and in the hills to the north, crushed and altered granitic rocks are overlain by several generations of Pleistocene alluvium. Clasts in the alluvial deposits north of the fault include Pelona Schist, volcanic rocks and rarely syenite. The original source of these clasts was probably Sierra Pelona and the Soledad Pass area to the south of the San Andreas fault but their immediate source is probably older alluvial deposits between the San Andreas and Punchbowl faults to the south.

4.5 Road crosses San Andreas fault at curve.

5.0 [Intersection with Longview Rd. Turn left to visit Devil's Punchbowl if time permits. The area is a county park with good access to outcrops via trails.] The relationship between the Punchbowl Formation of this area and that of Cajon Pass is important to an understanding of the fault offset. Were the two formations deposited in close proximity to each other?

5.0 [Turn right on Longview Rd.]

5.3 Road crosses San Andreas fault at highway marker 24.77. Tilting and minor faulting is conspicuous in old alluvial deposits exposed in cuts to the south of the main break.

6.1 [Intersection with Fort Tejon Rd; turn left (west); stay on Ft. Tejon Rd. for next 5 mi.] The hills to the north of the road are underlain by deeply weathered but essentially unfaulted granitic rocks.

11.2 [Turn left (west) onto Mt. Emma Rd.]

12.7 Road cuts expose pinkish sandstone of the Pliocene Anaverde Formation capped by gravel from Little Rock Creek. The Anaverde Formation crops out along the north side of the San Andreas fault for the next 28 mi.

13.1 Mt. Emma Rd. Stop

[Park at the east end of low ridge to south of road.]

The ridge consists of faulted Anaverde sandstone capped by gravel offset from Little Rock Creek. Walk to the crest of the ridge. Light colored boulders with large K-feldspar crystals are Lowe Granodiorite. Note gash-like swales formed by faulting, probably produced by severe shaking of ridge crests. The San Andreas fault extends along the south side of the ridge and crosses Mt. Emma Rd. in the area of the large fill (at highway marker 8.03), 0.3 mi. west of the parking area. Its trace, trending N63°W, can be seen for many miles in both directions. The course of Little Rock Creek to the northwest is offset about 1.5 mi. to the right; however, this is only a partial offset. Gravel containing boulders of Lowe Granodiorite and other rock types characteristic of the Little Rock Creek drainage area are exposed along the north side of the fault for as much as 7 miles to the east.

Follow the ridge crest west to the road. If time permits, look at the crushed granitic rock in the canyon bottom to the south of the fault.

13.7 Pliocene(?) sandstone and conglomerate are exposed in the cut on the right and gypsiferous siltstone and shale are exposed in the next cut west. These beds are mapped as Punchbowl Formation by Noble (1954) but are lithologically distinct from beds in Devil's Punchbowl and Cajon Valley. Part of this formation is lithologically similar to the Anaverde Formation but the two formations contain different clast assemblages and were probably deposited in separate basins, perhaps several miles apart. This formation contains abundant clasts of Pelona Schist, probably from Sierra Pelona

14.5 The road crosses Little Rock Creek which has a larger drainage area than any other stream flowing northward from the San Gabriel Mountains. Note the coarse gravel in the channel. The granitic ridge projecting up over 400 feet along the east side of the channel prevents Little Rock Creek from migrating eastward. Thus, the occurrence of Little Rock Creek gravel along the north side of the San Andreas fault to the east is the result of fault displacement.

14.7 [Intersection with Cheseboro Rd.; turn right (north).]
14.8 Fault in cut to west places altered granitic rocks on south against sedimentary rocks on north. Area capped by bouldery alluvium from Little Rock Creek.
15.4 [Turn left (west) on Barrel Springs Rd. and continue 0.6 mi.]

16.0 Barrel Springs Rd. Stop

The San Andreas trends along the canyon bottom to north. On the south is alluvium from the San Gabriel Mountains, including coarse gravel from Little Rock Creek. Walk onto the ridge spur directly north of the San Andreas. The lower part of the spur is underlain by southward dipping old alluvium containing syenite clasts identical to syenite exposed south of the fault about 5 miles west. Further north along the spur, older alluvium contains coarse clasts of Pelona Schist, including garnet-bearing types characteristic of eastern Sierra Pelona, 7 to 8 miles west. Similar old alluvium with Pelona Schist and syenite clasts occurs locally beneath Little Rock Creek gravels on the north side of the San Andreas fault as much as 3 miles further east; thus providing evidence for about 10 miles of right slip since the most easterly gravels were deposited. The Pelona Schist and syenite gravel can also be observed on the ridge crest on the east side of 47th St., 0.4 mi. west.

18.4 Barrel Springs Rd. crosses the California Aqueduct. Note the gate on the aqueduct which is designed to close if an earthquake causes the channel to rupture where it crosses the San Andreas fault a short distance east.
19.0 [Intersection with Pearblossom Highway; turn left and go 0.3 mi. south and park in broad area beyond aqueduct.] The San Andreas fault goes through the intersection.

19.3 Pearblossom Hignway Stop

The cut exposes old alluvium containing Pelona Schist gravel. Dark colored Pliocene(?) claystone (old lake deposits) has been injected upward along a fault near the center of the cut. The injection probably occurred during a single severe earthquake when the claystone was in a saturated condition. The Pelona Schist gravel undoubtedly came from Sierra Pelona, 4 to 6 miles west, but its position south of the San Andreas fault poses a problem. The absence of other clast types makes it unlikely that it was deposited by a stream draining eastward along the fault. It has probably been offset along the Nadeau fault to the south or it may have been deposited along the north side of the San Andreas fault, offset along the fault and then washed back onto the south side.

[Proceed 1.3 mi. south to Sierra Highway, turn right and continue 2.3 mi. to Una Lake.]

22.9 Una Lake Stop

Una Lake is a sag pond along the south side of the San Andreas fault. The compression ridge to the north consists of Pelona Schist gravel resting on faulted sandstone of the Anaverde Formation.

[Proceed 0.3 mi.; turn left on S St. and continue 1 mi. to freeway. Park on shoulder on either side of freeway access roads.]

24.3 Antelope Valley Freeway Stop

Walk northward along outside of freeway fence to top of hill. Climb the west side for evening viewing and the east side for morning viewing. Note low scarp along southern edge of hill. It was probably formed during the 1857 Fort Tejon Earthquake. From the top of the hill you can see folds and faults in the 'liocene Anaverde Formation exposed in he freeway cuts. Some of the faults ppear to offset the ground surface, uggesting that the structure is still volving. To what extent should develop- ent be restricted in areas such as this?

Syenite gravel, such as that observed o the north of the San Andreas fault everal miles east, can be seen in place y going 0.2 mi. west of the freeway on St. and then going south (left) on uyon St. for 0.4 mi. The ground is overed with syenite gravel derived from enhi Mtn., directly to the south. This s also a good place to collect syenite or comparison with that from the Orocopia ountains.

elona Schist is exposed about 2 miles est on S St.

Palmdale is 1.5 mi. north on the freeway.]

ALMDALE - SOLEDAD BASIN LOOP (62 miles ound trip)

The Soledad Basin contains the same istinctive basement formations as the rocopia Mountains and is believed to have een located directly southwest of the rocopia Mountains prior to displacement long the San Andreas fault.
From Palmdale take the Antelope Valley reeway (State 14) south 12 miles; turn ff on Crown Valley Rd. and go south past the town of Acton. Turn right on Soledad anyon Rd. and proceed 1.5 mi. south to econd series of outcrops and park near ighway marker 21.75.]

arker Mountain Stop

Parker Mountain is the most westerly exposure of the Lowe Granodiorite pluton, lescribed by Ehlig (this vol.). The horn- lende-bearing facies, typical of the luton's western margin, is exposed here. Other facies of the Lowe Granodiorite are est seen along Angeles Forest Highway. On the west side of Parker Mountain, the Oligocene - lower Miocene Vasquez Forma- tion contains coarse breccias derived from the hornblende-bearing facies.

[Continue 2.1 mi. southwest on Soledad Canyon Rd. then park.]

Soledad Canyon Stop

The white outcrops are of deeply weathered anorthosite similar to that exposed in Painted Canyon in the Mecca Hills. Anorthosite, and related gabbro and diorite underlie the region south of Soledad Canyon and can be observed in road cuts for the next several miles. The Soledad fault separates anorthosite from the Vasquez Formation exposed to the north. The fault was very active during deposition of the Vasquez Formation but has been inactive since late Miocene time and is not likely to reactivate because it is offset in several places by cross faults.

[Continue west on Soledad Canyon Rd. for another 10 miles. Pass under freeway (State 14) then turn right 0.4 mi. fur- ther onto Shadow Pines Blvd. Go 0.7 mi. to end and then 1 block west to Abelia Rd.; turn right and continue north 0.4 mi. to side road on right leading into Tick Canyon Wash. Park along wash.]

Tick Canyon Stop

The area is underlain by westward- dipping sandstone and conglomerate of the upper Miocene Mint Canyon Formation. Notice that most of the clasts in the conglomerate are of volcanic origin. A few of the clasts contain abundant pheno- crysts of mantled feldspar (rapakivi tex- ture). These clasts are derived from dikes near the northern end of the Choco- late Mountains. The other volcanic clasts are also characteristic of vol- canic rocks exposed in the Chocolate Mountains (see Ehlig and others, this vol.). Also, note channelling and clast imbrication indicating sediment transport from east to west.

[Return to Soledad Canyon Rd. and go 2 miles west to Sand Canyon Rd.; turn right and go 0.9 mi. north.]

Sand Canyon Pause Stop

The yellowish bed, about six inches thick exposed in the roadcut on left, contains tiny shells of fresh water clams. This part of the Mint Canyon Formation was deposited in a deltaic environment near the margin of a lake. Beds further east are entirely of fluvial origin. Beds of lacustrine origin are dominant in Boquet Canyon to the northwest and south of the Santa Clara River to the southwest.

[Continue 1 mile to Sierra Highway; turn right and go 3 miles north to area of basement exposures. Park near highway marker 40.48.]

Sierra Highway Stop

Augen gneiss crops out along sides of canyon. Note large ovoids of pink K-feldspar. Similar augen gneiss occurs in the eastern Orocopia Mountains to the east of the San Andreas fault and in the vicinity of Frazier Mountain to the west of the San Gabriel fault (Crowell, this vol.). Augen gneisses from all three areas yield concordant U-Pb ages of about 1670 m.y. (Silver, 1971).

[Continue northeast on Sierra Highway for 10 miles to freeway (State Highway 14). Pass over freeway and park on north side of Escondido Canyon Rd.]

Escondido Canyon Road Stop

Precambrian syenite is exposed in cuts along the south side of the road. Note similarity between this syenite and that exposed in the northwestern Orocopia Mountains.

[Return to Palmdale via State 14; distance 14 miles.]

PALMDALE TO LAKE OF THE WOODS

0.0 [From the freeway (State 14) go 1 mile northwest on Palmdale Blvd. and then go left on Elizabeth Lake Rd. Continue west to 5.6; park near highway marker 5.65. This stop is 2.2 mi. east of intersection with Godde Hill Rd.]

Leona Valley Stop

The San Andreas fault is exposed at the bend in the gully along Armagosa Creek to the north of the road. Here soil and alluvium are faulted against sandstone and conglomerate of the Pliocene Anaverde Formation. The scarp to the east of the gully was probably created, in part, during the 1857 Fort Tejon earthquake. A mile to the west th road runs along the base of a prominent scarp which is probably the product of numerous earthquakes.

[Continue 2.2 mi. west to intersection with Godde Hill Rd.]

Because of limited time, the field trip bypasses the next 30 miles of the San Andreas fault. For those who have the time, it is well worthwhile to continue along the fault to observe the numerous examples of topography modified by faulting.

[Turn right on Godde Hill Rd. and procee north across Portal Ridge.]

Portal Ridge is underlain by Pelona Schist as is Sierra Pelona, directly across the San Andreas fault to the sout. This occurrence of schist on opposite sides of the fault is probably fortuitou, as a result of its wide distribution. Similar schist occurs along the Garlock fault in the Tehachapi Mountains to the northwest and in the Rand Mountains to the north. Alternatively, the Hitchbroo fault along the north side of Portal Ridge might be a cut off segment of the San Andreas fault. In this case the schist of Portal Ridge would have originated south of the San Andreas, perhaps as a slice from Pelona Schist of Mount Pinos to the west of Frazier Park.

[North of Portal Ridge Godde Hill Rd. be comes Ave. 60. Go 12 miles north and turn left onto the Old Ridge Route (Coun ty Rd. N2) and follow the old concrete road 2.0 mi. up the hill and park.]

Old Ridge Route Stop (Fig. 6)

Examine the low-angle thrust that brings shattered gneiss and granite across sandstone and conglomerate of the Plio-Pleistocene Hungry Valley Formation. The thrust is cut by several splays from the San Andreas fault. Bald Mountain consists of a wedge-shaped mass of basement rock riding on faults that converge at depth. The thrust plate extends for a few miles and probably formed by downslope movement from a "mushrooming" basement wedge elevated in a strike-slip regime. The thrust plate is too large to be visualized as a simple landslide; moreover, there is no appropriate uphill source for the hanging-wall block.

[Go 0.2 mi. further; turn left on Pine Canyon Rd.; continue 0.7 mi. and park near highway marker 18.10.]

Pine Canyon Rd. Stop

Road cut contains vertical sandstone and conglomerate beds of the Ridge Basin Group faulted against shattered quartz monzonite. The fault consists of several feet of black gouge and contains phacoids of granitics and sediments. The main San Andreas fault is about a third of a mile north.

Go about 1/4 mi. around corner to turn around. Return to State 138 and continue west 2.7 mi. to the entrance to the Southern California Edison Bailey Substation. Stay right on Gormon Post Rd. where State 138 curves south.]

Bailey Substation Stop

The cut along the entrance road provides good exposures of the marine upper Miocene Quail Lake Formation, also referred to as the Santa Margarita Formation. Refer to Crowell (1952) and Dibblee (1967) for a description of the formation. It rests unconformably on the lower Miocene Neenach Volcanic Formation and on granitic rocks. No offset has been established for the Quail Lake Formation but the Neenach Volcanic Formation has been correlated with the Pinnacles Vol-

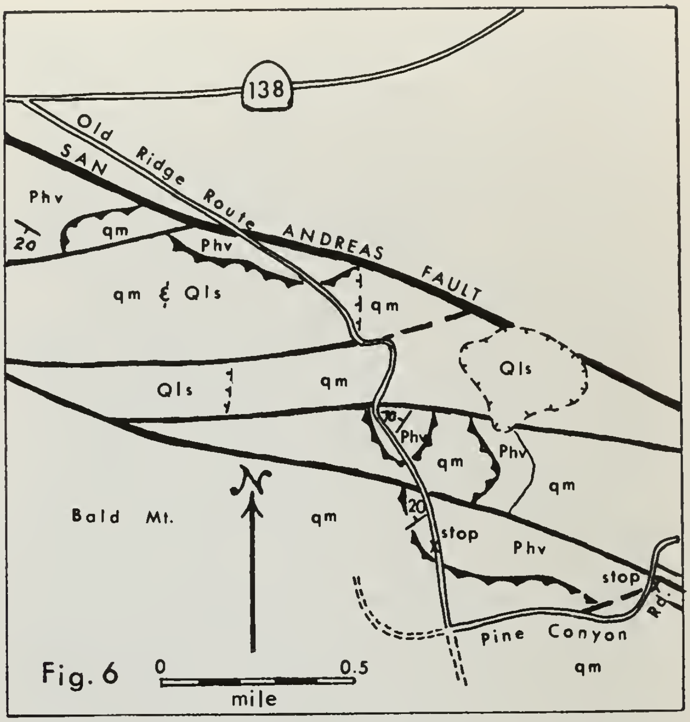


Fig. 6

canic Formation, from which it has been separated by 195 miles of right slip along the San Andreas fault (Matthews, 1973). The Neenach volcanics can be seen along the road in Pine Canyon, about 8 miles east.

[Proceed northwestward to Gorman.]

The road follows the San Andreas fault; notice the sagponds, scarps and other geomorphic evidence of recent faulting. Slices of purple volcanics lie within the fault zone. The Plio-Pleistocene Hungry Valley Formation crops out south of the fault zone and pink microcline granite with pendants of marble and hornfels crops out to the north. Gorman is precisely on the main strand of the San Andreas fault zone; note scarps in the topography to the northwest. Large landslides and small thrust masses, probably squeezed from the San Andreas zone, occur near the intersection of Gorman Post Road with Interstate 5.

[Pass under Interstate 5 and take frontage road 3 miles northwest to Frazier Mtn. Rd.]

The San Andreas fault crosses the road at the crest of Tejon Pass, 2 miles west of Gorman. High terraces to the west on the flank of Frazier Mountain correlate with other terrace remnants throughout this general region. The Garlock fault intersects the San Andreas fault a mile northwest of Tejon Pass. As you approach Frazier Mountain Rd., pause and look northeastward along the trace of the Garlock fault. It has not moved in this region as recently as the San Andreas fault, so that scarps and other fault landforms are lacking. Rocks to the south of the Garlock consist of pink coarse-grained microcline granite with pendants; those to the north consist of white fine-grained quartz monzonite with similar roof pendants of marble and hornfels. These northern rocks are thrust over gabbros and gneisses on the Pastoria thrust, an ancient movement zone which crosses Interstate 5 near Fort Tejon, north of our route. The Garlock fault probably has a total left slip of about 40 miles (Smith, 1962).

0.0 [Turn west along Frazier Mountain Rd.; continue past the town of Frazier Park to Lake of the Woods.]

For several miles along this stretch, the San Andreas fault has an east-west trend. The northwest-trending San Gabriel fault joins the San Andreas fault in this area but is not exposed at the surface. A wedge-shaped plate of Precambrian gneiss and migmatite, which constitutes Frazier Mountain to the south, has been thrust southeastward across the trace of the San Gabriel fault (Crowell, this vol.).

[Park on Frazier Mtn. Rd. 0.3 mi. beyond its intersection with Cuddy Valley Rd.]

7.0 Lake of the Woods Stop

Augen gneiss is exposed to the right of the road. Note the similarity between it and augen gneiss observed along Sierra Highway in the Soledad Basin. The gneiss at this location is probably a fault slice within the Big Pine fault zone. The main exposures of augen gneiss are on Frazier Mountain to the southeast (Crowell, this vol.).

The east-west trending Big Pine fault intersects the San Andreas fault northeast of the junction of Frazier Mtn. Rd. and Cuddy Valley Rd. A few miles west of here, the Oligocene-lower Miocene Plush-Ranch Formation contains coarse breccia beds along the north side of the Big Pine fault indicating the fault was active at that time (Bohannon, this vol.). In addition to vertical dis placement the Big Pine fault probably ha about 8 miles of left slip along it (Carman, 1964).

[Refer to Crowell (this vol.) for a fiel guide along the San Andreas fault betwee here and the Carizzo Plains.]

[Return to Gorman.]

GORMAN TO CASTAIC

0.0 [Proceed southward on Interstate Highway 5 at Gorman.]
3.7 [Take Quail Lake turnoff onto frontage road along west side of freewa and continue south 0.8 mi. Park at the south end of the long cut.]

4.5 Peace Valley Stop

White conglomeratic sandstone and greenish siltstone of the Pliocene Hungry Valley Formation lie unconformably upon quartz monzonite which is exposed in the core of an anticline. The unconformity can be clearly traced to th west around the plunging nose of the anticline. On the southwest, however, strata of the underlying Peace Valley beds, including coarse sedimentary breccias, abut against the folded basement at a high angle. The subsurface trace of the Liebre fault bounds this basement anticline on the south.

The unconformity exposed in the road cut is a "skidded" unconformity characterized by a foot of gouge. In fact, all rocks here are crushed and disturbed: the quartz monzonite is

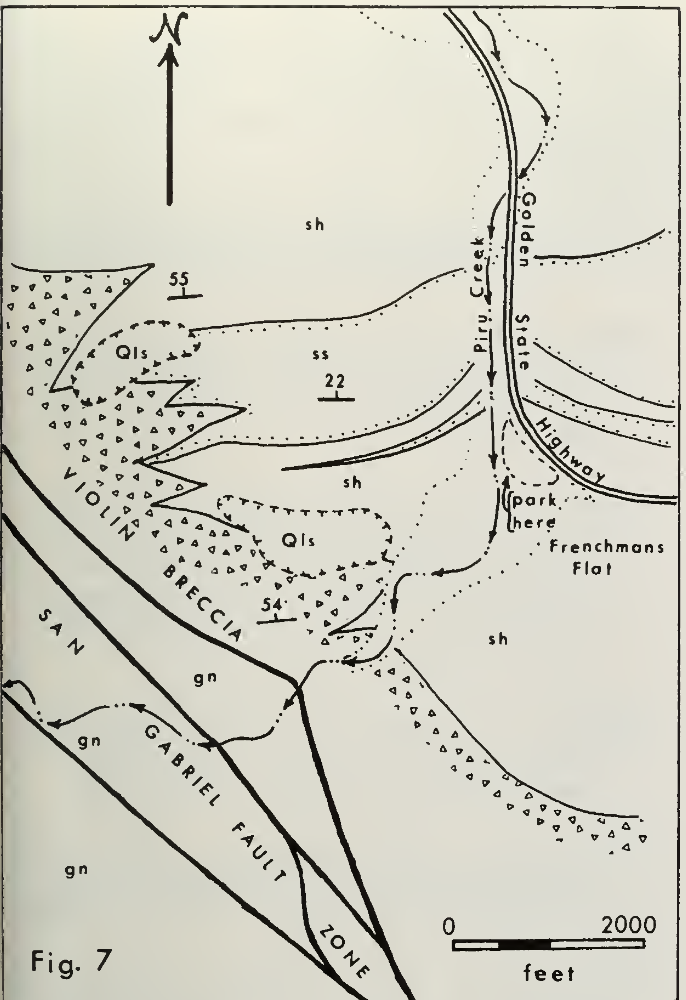


Fig. 7

fractured and at places comminuted; the Hungry Valley strata are faulted, phacoided, and folded. The outcrop lies between the San Andreas fault and the plunging end of the Liebre Mountain anticline on the south.

[Return to Interstate 5 and proceed south.]

Between here and Castaic, Interstate 5 crosses the axial part of the Ridge Basin which contains about 29,000 feet of upper Miocene and Pliocene strata of the Ridge Basin Group. The lowermost 2000 feet of the group is marine but the bulk of the section is of fluvial and lacustrine origin. Ridge Basin is along the northeast side of the San Gabriel fault and its formation is no doubt related to major right slip on the San Gabriel fault. Refer to Crowell (this vol.) for details.

20.1 [Turnoff on Templin Highway and proceed 0.3 mi. west; turn right (north) on Golden State Highway; continue 5.0 mi. Park in Frenchmans Flat campground on west side of road and walk down Piru Creek into the gorge (Fig. 7).

25.4 Frenchmans Flat Stop

The great thickness of northward-dipping sandstone and shale, which is exposed along the highway, grades abruptly into the Violin Breccia to the west (Crowell, this vol.). The Violin Breccia, a part of the Ridge Basin group which consists of a rubble of gneiss blocks as much as 6 feet in diameter in a muddy matrix, accumulated as talus or alluvial debris or mudflows at the base of the San Gabriel fault scarp. It crops out for 20 miles along the northeast side of the San Gabriel fault and has a stratigraphic thickness of over 35,000 feet but extends along strike to the east a maximum distance of 5,000 feet.

Examine the change in bedding characteristics and sedimentary structures as you cross the facies transition from shale to breccia and approach the San Gabriel fault. The main fault is exposed on the north side of the gorge, where about two inches of coherent gouge or cataclasite crops out in a gully. Here comminuted granitic and gneissic rocks are brought against Violin Breccia. Basement rock on down the canyon is severely deformed and the fault zone is actually broad and contains several slices.

Formations older than 10 to 12 million years are offset by about 35 to 40 miles to the right along the San Gabriel fault (Crowell, this vol; Ehlig and others, this vol.). During the Pliocene, the San Gabriel fault was probably the main strand of the San Andreas in this area. There is little evidence to indicate that the presently active strand of the San Andreas fault bounding Ridge Basin on the northeast was active at the same time as the San Gabriel fault.

[Return to Templin Highway.]
0.0 [Pass under Interstate 5 and follow Templin Highway north to Old Ridge Route; park 0.2 mi. north of intersection.]

1.3 Old Ridge Route Stop

Overview of Ridge Basin. Note structure and overlap relations to the north and east along Castaic Canyon. Roadcuts in the vicinity display alluvial and lacustrine sedimentary features. Of particular interest are severely disturbed and contorted layers, perhaps formed during sliding on subaqueous slopes as a result of either tectonic oversteepening (during earthquakes?) or sedimentary overloading. Walk southward as much as 1/4 mile along the Old Ridge Route and examine these sedimentary features.

[Continue northeastward down Templin Highway to the bridge across Castaic Creek. Park east of the bridge.]

5.2 Castaic Creek Stop

The unconformity at the base of the Ridge Basin Group is well marked in the walls of Castaic Canyon about one-third of a mile up the canyon from the bridge. The Paleocene San Francisquito Formation underlies the Ridge Basin Group in this area.

[The guide ends here. It is about an hours drive to Los Angeles via Interstate 5.]

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CALIFORNIA DIVISION OF MINES AND GEOLOGY
JAMES E. SLOSSON, STATE GEOLOGIST

STATE OF CALIFORNIA
THE RESOURCES AGENCY
DEPARTMENT OF CONSERVATION

PRELIMINARY FAULT AND GEOLOGIC MAP OF SOUTHERN CALIFORNIA

Reprinted from Preliminary Report 13 (1973)

This preliminary map is published to satisfy the urgent demand for an up-to-date, comprehensive fault map of California. It was made largely from pen-and-ink tracings of the original compilation. This preliminary map will be followed by a Fault Map and a Geologic Map of California. These maps will show essentially the same data as this preliminary map but the lines will be scribed, the symbols and lettering type-set, and the geologic units on the Geologic Map will be in color. Hence the later maps will be more legible; they will also be accompanied by a text and source index.

SCALE 1:750,000

(1 inch equals approximately 12 miles)

10 0 10 20 30 40 Miles

10 0 10 20 30 40 50 Kilometers

Submarine contour interval : 100 fathoms

COMPILED BY
CHARLES W. JENNINGS
WITH ASSISTANCE FROM
R.G. Strand, T.H. Rogers, M.C. Stinson, J.L. Burnett, J.E. Kahle and R. Streitz
GEOLOGIC GRAPHICS BY R.R. Moar and R.A. Switzer

STRATIGRAPHIC SYMBOLS

CENOZOIC SEDIMENTARY ROCKS

Q	Alluvium (mostly Holocene, some Pleistocene); Pleistocene nonmarine; Quaternary marine
Qls	Selected large landslides
Qg	Glacial deposits
Qs	Dune sand (selected large sand deposits generally near coast or playas)
QPc	Plio-Pleistocene nonmarine; Pliocene nonmarine
P	Pliocene marine
M	Miocene marine
Mc	Miocene nonmarine
Φ	Oligocene marine
Φc	Oligocene nonmarine
E	Eocene marine
Ec	Eocene nonmarine
Ep	Paleocene marine
Tc	Tertiary nonmarine

VOLCANIC ROCKS

Qrv	Holocene (Recent) volcanic rocks
QrvP	Holocene (Recent) pyroclastic rocks including volcanic mudflow deposits
Qv	Quaternary volcanic rocks
QvP	Quaternary pyroclastic rocks including volcanic mudflow deposits
Tv	Tertiary volcanic flow rocks or undivided flow and pyroclastic rocks
TvP	Tertiary pyroclastic rocks including volcanic mudflow deposits
Ti	Tertiary intrusive rocks

PRE-CENOZOIC SEDIMENTARY AND METAMORPHIC ROCKS

TK	Coastal belt marine sedimentary rocks. Is included by some in the Franciscan Formation. Previously considered Cretaceous but now known to also contain early Tertiary microfossils
K	Cretaceous marine, undivided (includes some nonmarine strata)
Ku	Upper Cretaceous marine
Kl	Lower Cretaceous marine
KJf	Franciscan assemblage (Predominantly sedimentary and metasedimentary rocks. Includes Franciscan melange except where separated—see below)
KJf_m	Franciscan melange of fragmented and sheared rocks
KJf_s	Franciscan schist (Blueschist and semi-schist)
J	Jurassic marine including Knoxville Formation
Ŧ	Triassic marine
Pm	Permian marine
C	Carboniferous marine
D	Devonian marine
SO	Silurian and/or Ordovician marine
Є	Cambrian marine
m	Metamorphic rocks of Pre-Tertiary age, undivided
ls	Limestone and marble of Pre-Tertiary age
sch	Schist of Pre-Tertiary age
Pz	Paleozoic marine, undivided (includes some Triassic rocks in Klamath Mountains area)
pЄ	Precambrian rocks, undivided

METAVOLCANIC ROCKS

Mzv	Mesozoic metavolcanic rocks (including Franciscan volcanic rocks)
Pzv	Paleozoic metavolcanic rocks
mv	Pre-Tertiary metavolcanic rocks

PLUTONIC ROCKS

gr^{Cz}	Cenozoic granitic rocks
gr^{Mz}	Mesozoic granitic rocks
gr^{Pz}	Paleozoic (including Permo-Triassic) granitic rocks
$gr^{pЄ}$	Precambrian granitic rocks including anorthosite and gabbro of San Gabriel Mtns
gr	Granitic rocks of uncertain age
gb	Gabbroic and some dioritic rocks chiefly of Mesozoic age
um	Ultramafic rocks

UNDIVIDED

grm	Pre-Tertiary granitic and metamorphic rocks, undivided
pЄc	Complex of Precambrian igneous and metamorphic rocks, may be Mesozoic in part

FAULT SYMBOLS

Onshore Faults (For color code, see below)

Dashed line where fault location is approximate or inferred; dotted where fault is concealed by younger rocks or by lakes or bays; queried where continuation or existence of fault is uncertain. Many concealed faults in the Great Valley are based on subsurface maps of various selected horizons and locations shown are often approximate; they may be indicative of structural trend only.

Offshore Faults (For color code, see below)

Faults indicated by acoustic-reflection profiling records; location approximate. Long dashes where record of fault is well defined, short dashes where records are less well defined or fault inferred, queried where continuation is uncertain.

Topographic lineament indicated on bathymetric charts. May represent possible fault or fault zone. (Shown south of Pt. Conception only).

FAULT CLASSIFICATION COLOR CODE
(Indicating Recency of Movement)

Fault having moved during historic time (approximately 200 years) and associated with one or more of the following:

(a) a recorded earthquake with surface rupture. (Also included are some well defined surface breaks caused by ground-shaking during earthquakes e.g. extensive ground breakage not on the White Wolf fault caused by Arvin-Tehachapi earthquake of 1952.) Date of associated earthquake indicated. Where repeated surface ruptures on same fault have occurred, only the date of latest movement may be indicated, especially if earlier reports are not well documented as to location of ground breaks.

1836 ▶ ◀ 1836 — A triangle to the right or left of the date indicates termination point of surface displacement.

▶ 1922 ◀ — Date bracketed by triangles indicates local fault break.

1906 — No triangle by date indicates an intermediate point along fault break.

(b) fault creep slippage—slow ground displacement usually without accompanying earthquakes. Red dot on fault indicates location where fault creep slippage has been observed and recorded.

1969; 1968 ■ ■ 1968 — Red square on fault indicates where fault creep slippage has occurred that has been triggered by an earthquake on some other fault. Date of causitive earthquake indicated. Red squares to right and left of date indicate terminal points between which triggered creep slippage has occurred (creep either continuous or intermittent between these end points).

(c) displaced survey lines

Quaternary fault displacement (during past 2 million years), without historic (approximately 200 years) record. Recognized by scarps in alluvium, terraces, or other Quaternary units; off-set stream courses; alignment of sag depressions, fault troughs, and fault saddles; markedly linear steep mountain fronts (associated with an adjacent concealed fault trace). Includes concealed fault-controlled ground water barriers in Quaternary sediments as indicated by well data. (Note: Where local evidence indicates that a fault has moved during Quaternary time, the entire length of the fault is shown as Quaternary unless contrary evidence is available).

Pre-Quaternary fault (older than 2 million years) or fault without recognized Quaternary movement. (Note: Some faults shown bounding Quaternary rocks and older rocks are included in the pre-Quaternary category because the source of mapping used was of reconnaissance nature or the mapping was not done with the object of dating fault movements).

Faults shown in this category should not necessarily be considered "dead". Evidence for recency of movement may not have been observed or it may be lacking because the fault may not be in contact with Quaternary deposits. In many cases the evidence may have been destroyed by erosion, or covered by vegetation or by works of man.

SPECIAL FAULT NOTATIONS

U — Upthrown side (relative or apparent).

D — Downthrown side (relative or apparent).

Arrows along fault indicate relative or apparent direction of lateral movement.

QPc {Plio-Pleistocene nonmarine / Pliocene nonmarine}
P Pliocene marine
M Miocene marine
Mc Miocene nonmarine
Φ Oligocene marine
Φc Oligocene nonmarine
E Eocene marine
Ec Eocene nonmarine
Ep Paleocene marine
Tc Tertiary nonmarine

VOLCANIC ROCKS

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QrvP Holocene (Recent) pyroclastic rocks including volcanic mudflow deposits
Qv Quaternary volcanic rocks
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Tv Tertiary volcanic flow rocks or undivided flow and pyroclastic rocks
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KJfm Franciscan melange of fragmented and sheared rocks
KJfs Franciscan schist (Blueschist and semischist)

J Jurassic marine including Knoxville Formation
Tr Triassic marine
Pm Permian marine
C Carboniferous marine
D Devonian marine
SO Silurian and/or Ordovician marine
Є Cambrian marine
m Metamorphic rocks of Pre-Tertiary age undivided
ls Limestone and marble of Pre-Tertiary age
sch Schist of Pre-Tertiary age
Pz Paleozoic marine undivided (includes some Triassic rocks in Klamath Mountains area)
pЄ Precambrian rocks undivided

METAVOLCANIC ROCKS

Mzv Mesozoic metavolcanic rocks (including Franciscan volcanic rocks)
Pzv Paleozoic metavolcanic rocks
mv Pre-Tertiary metavolcanic rocks

PLUTONIC ROCKS

grCz Cenozoic granitic rocks
grMz Mesozoic granitic rocks
grPz Paleozoic (including Permo-Triassic) granitic rocks
grpЄ Precambrian granitic rocks including anorthosite and gabbro of San Gabriel Mtns
gr Granitic rocks of uncertain age
gb Gabbroic and some dioritic rocks chiefly of Mesozoic age
um Ultramafic rocks

UNDIVIDED

grm Pre-Tertiary granitic and metamorphic rocks undivided
pЄc Complex of Precambrian igneous and metamorphic rocks may be Mesozoic in part

FAULT SYMBOLS

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1969 1968■ ■1968 Red square on fault indicates where fault creep slippage has occurred that has been triggered by an earthquake on some other fault. Date of causitive earthquake indicated. Red squares to right and left of date indicate terminal points between which triggered creep slippage has occurred (creep either continuous or intermittent between these end points).

(c) displaced survey lines

Quaternary fault displacement (during past 2 million years), without historic (approximately 200 years) record. Recognized by scarps in alluvium, terraces, or other Quaternary units; off-set stream courses; alignment of sag depressions, fault troughs, and fault saddles; markedly linear steep mountain fronts (associated with an adjacent concealed fault trace). Includes concealed fault-controlled ground water barriers in Quaternary sediments as indicated by well data. (Note: Where local evidence indicates that a fault has moved during Quaternary time, the entire length of the fault is shown as Quaternary unless contrary evidence is available).

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SPECIAL FAULT NOTATIONS

U Upthrown side (relative or apparent).

D Downthrown side (relative or apparent).

Arrows along fault indicate relative or apparent direction of lateral movement.

Arrow on fault indicates direction of dip of fault surface.

Thrust fault (barbs on the relatively overthrust block). Fault surface generally dipping less than 45° but locally may have been steepened. Coast Range Thrust is generally modified by later folding and faulting and locally is very steep.

OTHER SYMBOLS

Geologic boundary, dashed where inferred or extrapolated from limited data.

Volcano of Quaternary or Pliocene age.

NOTES

This map is based on a generalization of the 1:250,000 scale Geologic Atlas of California (1958-1969), but has been extensively updated with new information in many areas. A fault classification color code has been added.

Users of this map should be aware that active faults and earthquakes are the subject of very intensive research and that refinements of the interpretations given here are sure to come within a few years. Therefore, this map should be considered a provisional inventory of faults in California. Revised editions of this map are planned in order to keep abreast of new data and to impart this information to geologists, engineers, planners, and others who use this map.

Persons having additional pertinent data concerning faults of this area are urged to notify C. W. Jennings, California Division of Mines & Geology, Ferry Building, San Francisco, 94111, in order that future editions may be corrected.

THE PREPARATION OF THIS MAP WAS FINANCED IN PART THROUGH A COMPREHENSIVE PLANNING GRANT FROM THE DEPARTMENT OF HOUSING AND URBAN DEVELOPMENT, UNDER THE PROVISIONS OF SECTION 701 OF THE HOUSING ACT OF 1968, AS AMENDED

TOPOGRAPHIC BASE MAP BY U.S. GEOLOGICAL SURVEY, 1970
This map is a reduction of a 1:500,000-scale published map.